



Consensus on diagnosis and management of Cushing's disease: a guideline update

Maria Fleseriu, Richard Auchus, Irina Bancos, Anat Ben-Shlomo, Jerome Bertherat, Nienke R Biermasz, Cesar L Boguszewski, Marcello D Bronstein, Michael Buchfelder, John D Carmichael, Felipe F Casanueva, Frederic Castinetti, Philippe Chanson, James Findling, Mônica Gadelha, Eliza B Geer, Andrea Giustina, Ashley Grossman, Mark Gurnell, Ken Ho, Adriana G Ioachimescu, Ursula B Kaiser, Niki Karavitaki, Laurence Katznelson, Daniel F Kelly, André Lacroix, Ann McCormack, Shlomo Melmed, Mark Molitch, Pietro Mortini, John Newell-Price, Lynnette Nieman, Alberto M Pereira, Stephan Petersenn, Rosario Pivonello, Hershel Raff, Martin Reincke, Roberto Salvatori, Carla Scaroni, Ilan Shimon, Constantine A Stratakis, Brooke Swearingen, Antoine Tabarin, Yutaka Takahashi, Marily Theodoropoulou, Stylianos Tsagarakis, Elena Valassi, Elena V Varlamov, Greisa Vila, John Wass, Susan M Webb, Maria C Zatelli, Beverly M K Biller

Cushing's disease requires accurate diagnosis, careful treatment selection, and long-term management to optimise patient outcomes. The Pituitary Society convened a consensus workshop comprising more than 50 academic researchers and clinical experts to discuss the application of recent evidence to clinical practice. In advance of the virtual meeting, data from 2015 to present about screening and diagnosis; surgery, medical, and radiation therapy; and disease-related and treatment-related complications of Cushing's disease summarised in recorded lectures were reviewed by all participants. During the meeting, concise summaries of the recorded lectures were presented, followed by small group breakout discussions. Consensus opinions from each group were collated into a draft document, which was reviewed and approved by all participants. Recommendations regarding use of laboratory tests, imaging, and treatment options are presented, along with algorithms for diagnosis of Cushing's syndrome and management of Cushing's disease. Topics considered most important to address in future research are also identified.

Introduction

Cushing's disease, the most common cause of endogenous Cushing's syndrome, is caused by an adrenocorticotrophic hormone (ACTH)-secreting pituitary tumour.¹ Optimal patient outcomes require accurate diagnosis, careful treatment selection, and management of the disease and its associated comorbidities to optimise patient outcomes.² Notably, compared with patients with adrenal causes of Cushing's syndrome, long-term quality of life is worse for patients with Cushing's disease.³ Since the publication of clinical guidelines in 2003,⁴ 2008,^{5,6} and 2015,⁷ novel screening and diagnostic modalities have been identified and new treatments approved for use. These new developments highlight the need for updates to clinical guidelines on this challenging disorder.

The Pituitary Society convened a 2-day virtual consensus workshop in October, 2020, to discuss management of Cushing's disease, critically review current literature, and provide recommendations for screening and diagnosis; optimal use of and monitoring outcomes from surgery, medical therapy, and radiation therapy; and identification and management of disease-related and treatment-related complications. The focus was on pituitary, rather than adrenal or ectopic Cushing's syndrome, and overlapping topics that had been recently covered in other consensus statements or reviews were not included.

This guideline update reviews recent evidence and recommendations for clinical practice, grading the quality of the evidence and the strength of the consensus recommendations. Key considerations for use of different laboratory tests and medical therapies are presented in the tables. Consensus recommendations for the diagnosis and monitoring of Cushing's syndrome, management of Cushing's disease

complications, and use of medical therapy for Cushing's disease are presented in the panels. Grading schema^{8,9} for quality of evidence and strong or discretionary recommendations are presented in the appendix (p 3). Algorithms for diagnosis of Cushing's syndrome (figure 1) and management of Cushing's disease are also presented.

Recommendations for adults with Cushing's disease are presented for use in clinical practice but should be considered alongside patient-specific and disease-specific factors for personalised care. A brief section regarding unique considerations in paediatric Cushing's disease is also included.

Methods

Workshop co-chairs and steering committee members identified 28 discrete topics related to Cushing's disease diagnosis, complications, and treatment to be addressed. Methods for critical review of the literature, pre-workshop lectures, and workshop discussions are described in the appendix.

Diagnosis of Cushing's syndrome: screening, confirmatory, and localisation modalities

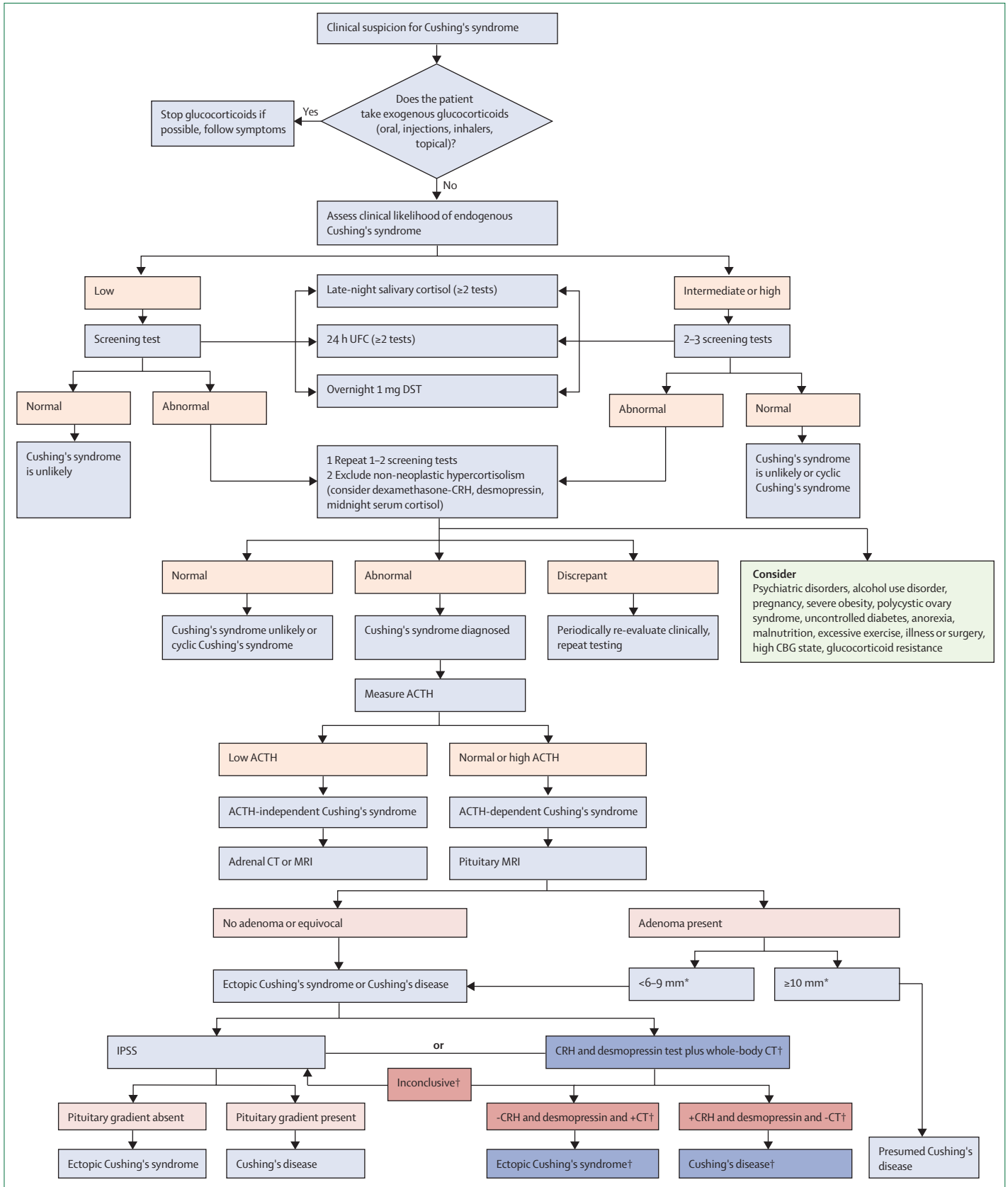
Laboratory tests

Diagnosis of Cushing's syndrome is often delayed for years, partly because of lack of awareness of the insidious, progressive disease process and testing complexity.¹⁰ Screening and diagnostic tests for Cushing's syndrome assess cortisol secretory status: abnormal circadian rhythm with late-night salivary cortisol (LNSC), impaired glucocorticoid feedback with overnight 1 mg dexamethasone suppression test (DST) or low-dose 2-day dexamethasone test (LDDT), and increased bioavailable

Lancet Diabetes Endocrinol
2021; 9: 847-75

Published Online
October 20, 2021
[https://doi.org/10.1016/S2213-8587\(21\)00235-7](https://doi.org/10.1016/S2213-8587(21)00235-7)

Oregon Health & Science University, Portland, OR, USA (Prof M Fleseriu MD, E V Varlamov MD); University of Michigan, Ann Arbor, MI, USA (Prof R Auchus); Mayo Clinic, Rochester, MN, USA (I Bancos MD); Cedars-Sinai Medical Center, Los Angeles, CA, USA (A Ben-Shlomo MD, Prof S Melmed MD); Université de Paris, Assistance Publique-Hôpitaux de Paris, Centre de Référence Maladies Rares de la Surrénale, Service d'Endocrinologie, Hôpital Cochin, Paris, France (Prof J Bertherat MD); Leiden University Medical Center and European Reference Center for Rare Endocrine Conditions (Endo-ERN), Leiden, Netherlands (Prof NR Biermasz MD, Prof A M Pereira MD); Federal University of Parana, Curitiba, Brazil (Prof C L Boguszewski MD); University of Sao Paulo, Sao Paulo, Brazil (Prof M D Bronstein MD); University Hospital Erlangen, Erlangen, Germany (Prof M Buchfelder MD); Keck School of Medicine, University of Southern California, Los Angeles, CA, USA (J D Carmichael MD); Santiago de Compostela University and Ciber OBN, Santiago de Compostela, Spain (Prof F F Casanueva MD); Aix Marseille Université, Marseille Medical Genetics, INSERM, Marseille, France (Prof F Castinetti PhD); Assistance Publique Hopitaux de Marseille, Marseille, France (Prof F Castinetti); Department



cortisol with 24-h urinary free cortisol (UFC; panel 1).^{5,6,11,12} In this setting, sensitivity of all tests is higher than 90%; the highest sensitivity rates are obtained with DST and LNSC and the lowest with UFC. Specificity is somewhat lower than sensitivity, with LNSC being the most specific and DST and UFC the least specific.^{12,13}

LNSC

The diagnostic utility of LNSC is based on the assumption that patients with Cushing's syndrome lose the normal circadian nadir of cortisol secretion;^{14,15} at least two or three LNSC tests are recommended.^{5,16} Patients with mild Cushing's syndrome may have LNSC just above the upper limit of normal (ULN). Sampling saliva at usual bedtime rather than at midnight could decrease false-positive results,¹⁷ as cortisol nadir is tightly entrained to sleep onset. Liquid chromatography tandem mass spectrometry can detect both cortisol and cortisone, thereby identifying contamination from topical hydrocortisone preparations, which typically do not contain cortisone. Thus, specificity is higher when using mass spectrometry while immunoassay has higher sensitivity for Cushing's syndrome.¹⁸ Multiple, periodic, sequential LNSC tests are particularly useful for the longitudinal surveillance needed in distinguishing patients with cyclic Cushing's syndrome who exhibit weeks to months of normal cortisol secretion interspersed with episodes of cortisol excess.¹⁹ By contrast, LNSC should not be done in patients with disruption of the normal day and night cycle, such as night-shift workers.^{14,15}

Overnight 1-mg DST

In healthy individuals, a supraphysiological dexamethasone dose inhibits vasopressin and ACTH secretion, thereby decreasing cortisol concentrations. Thus, a serum cortisol concentration of less than 1.8 µg/dL (50 nmol/L) at 0800 h in the morning after 1 mg dexamethasone given between 2300 h and midnight is considered to be a normal response.⁵ A negative result strongly predicts absence of Cushing's syndrome. At higher cutoff points (eg, 5 µg/dL [138 nmol/L]), DST sensitivity is reduced.¹² Cortisol concentrations of less than 1.8 µg/dL excludes dysregulated cortisol production from an adrenal incidentaloma;²⁰ in this setting, values higher than 5 µg/dL generally identify patients with dysregulated cortisol secretion from an incidentaloma with overt Cushing's

Figure 1: Algorithm for diagnosis of Cushing's syndrome

ACTH=adrenocorticotropic hormone. CBG=corticosteroid-binding globulin; CRH=corticotropin-releasing hormone. DST=dexamethasone suppression test. IPSS=inferior petrosal sinus sampling. UFC=urinary free cortisol. *There is consensus that all patients with lesions smaller than 6 mm in diameter should have IPSS and those with lesions of ≥10 mm do not need IPSS, but expert opinions differed for lesions 6–9 mm in diameter. †This alternative option does not have clear consensus and needs further research, and this is indicated by darker boxes. Green boxes indicate points to consider; darker colours indicate less validated testing pathways.

Panel 1: Clinical considerations and recommendations for Cushing's syndrome diagnosis and monitoring of Cushing's disease recurrence

If Cushing's syndrome is suspected:

- Start with urinary-free cortisol (UFC), late-night salivary cortisol (LNSC), or both; dexamethasone suppression test (DST) could also be an option if LNSC not feasible
- Multiple LNSC might be easier for patient collection

If confirming Cushing's syndrome:

- Can use any test
- UFC average two-to-three collections
- LNSC (two or more tests)
- DST useful in shift workers, not in women on oestrogen-containing oral contraceptives
- Measuring dexamethasone concentration, with cortisol concentration, the morning after 1 mg dexamethasone ingestion improves test interpretability

If Cushing's syndrome due to adrenal tumour is suspected:

- Start with DST
- LNSC has lower specificity in these patients

Monitoring for recurrence:

- Consider which tests were abnormal at initial diagnosis
- LNSC most sensitive, should be done annually
- DST and UFC usually become abnormal after LNSC
- UFC is usually the last to become abnormal

syndrome. False positive results might be seen with rapid absorption or malabsorption of dexamethasone due to increased gut transit time, chronic diarrhoea, or coeliac disease; from concomitant treatment with CYP3A4 inducers (eg, phenobarbital, carbamazepine, St John's wort); and from increased corticosteroid-binding globulin (CBG) concentrations caused by oral oestrogens, pregnancy, or chronic active hepatitis, which can increase total cortisol concentrations.^{21–23} Measuring dexamethasone concomitantly with cortisol, using laboratory-specific ranges of expected values, can reduce the risk for false-positive results.^{24,25} False-negative results are less common, typically resulting from inhibition of dexamethasone metabolism by concomitant medications such as fluoxetine, cimetidine, or diltiazem, leading to a higher biologically available dose. Decreased CBG and albumin concentrations, which can be noted in patients with concurrent nephrotic syndrome, also might produce a falsely low value.²⁶

UFC

At least two or three 24-h urine collections are advised to measure UFC to account for intra-patient variability.^{5,27} One advantage with UFC over DST is that overall cortisol production is independent of CBG changes and dexamethasone metabolism or compliance. However, although calculating the mean of several collections aids

of Endocrinology, La Conception Hospital, Marseille, France (Prof F Castinetti); Université Paris-Saclay, Assistance Publique-Hôpitaux de Paris, Hôpital Bicêtre, Le Kremlin-Bicêtre, France (Prof P Chanson MD); Medical College of Wisconsin, Milwaukee, WI, USA (Prof J Findling MD, Prof H Raff PhD); Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil (Prof M Gadelha MD); Memorial Sloan-Kettering Cancer Center, New York, NY, USA (E B Geer MD); San Raffaele Vita-Salute University, Milan, Italy (Prof A Giustina MD, Prof P Mortini MD); University of London, London, UK (Prof A Grossman MD); University of Oxford, Oxford, UK (Prof A Grossman); University of Cambridge, Cambridge, UK (Prof M Gurnell PhD); NIHR Cambridge Biomedical Research Center, Cambridge, UK (Prof M Gurnell); Addenbrooke's Hospital, Cambridge, UK (Prof M Gurnell); The Garvan Institute of Medical Research, Sydney, NSW, Australia (Prof K Ho MD, A McCormack PhD); Emory University School of Medicine, Atlanta, GA, USA (Prof A G Ioachimescu MD); Brigham & Women's Hospital, Boston, MA, USA (Prof U B Kaiser MD); Harvard Medical School, Boston, MA, USA (Prof U B Kaiser); Institute of Metabolism and Systems Research, College of Medical and Dental Sciences, University of Birmingham, Birmingham, UK (N Karavitaki PhD); Centre for Endocrinology, Diabetes and Metabolism, Birmingham Health Partners, Birmingham, UK (N Karavitaki); Department of Endocrinology, Queen Elizabeth Hospital, University Hospitals Birmingham NHS Foundation Trust, Birmingham, UK (N Karavitaki); Stanford University, Stanford, CA, USA (Prof L Katznelson MD); Pacific Neuroscience Institute, Santa Monica, CA, USA (Prof D F Kelly MD); Centre Hospitalier de l'Université de Montréal, Montréal, QC, Canada (Prof A Lacroix MD); Northwestern University Feinberg School of Medicine, Chicago, IL, USA

(Prof M Molitch MD); University of Sheffield, Sheffield, UK (Prof J Newell-Price PhD); National Institutes of Health, Bethesda, MD, USA (L Nieman MD, Prof C A Stratakis MD); ENDOC Center for Endocrine Tumors, Hamburg, Germany and University of Duisburg-Essen, Essen, Germany (Prof S Petersenn MD); Università Federico II di Napoli, Naples, Italy (Prof R Pivonello MD); Advocate Aurora Research Institute, Aurora St. Luke's Medical Center, Milwaukee, WI, USA (Prof H Raff); Department of Medicine IV, University Hospital of LMU, Ludwig-Maximilians-Universität, Munich, Germany (Prof M Reincke MD, Prof M Theodoropoulou PhD); Johns Hopkins University, Baltimore, MD, USA (Prof R Salvatori MD); University of Padova, Padova, Italy (Prof C Scaroni MD); Rabin Medical Center, Beilinson Hospital, Petah-Tikva, Israel (Prof I Shimon MD); Massachusetts General Hospital, Boston, MA, USA (Prof B Swearingen MD, Prof B M K Biller MD); CHU de Bordeaux, Hôpital Haut Lévéque, University of Bordeaux, Bordeaux, France (Prof A Tabarin MD); Nara Medical University, Kashihara, Japan (Prof Y Takahashi MD); Evangelismos Hospital, Athens, Greece (S Tsagarakis MD); Endocrinology Unit, Hospital General de Catalunya, Barcelona, Spain (E Valassi MD); Research Center for Pituitary Diseases (CIBERER Unit 747), Hospital Sant Pau, Barcelona, Spain (E Valassi, Prof S M Webb); Medical University of Vienna, Vienna, Austria (G Vila MD); Churchill Hospital, Oxford, United Kingdom (Prof J Wass MD); Universitat Autònoma de Barcelona, Barcelona, Spain (Prof S M Webb); University of Ferrara, Ferrara, Italy (Prof M C Zatelli MD)

Correspondence to: Prof Maria Fleseriu
Pituitary Center, Departments of Medicine and Neurological Surgery, Oregon Health & Science University, 3303 South Bond Ave Portland, OR 97239, USA
fleseriu@ohsu.edu

See Online for appendix

in correct interpretation, random variability can be as high as 50%.²⁸ As with LNSC, UFC relies on accurate collection by the patient.

Sex, body-mass index (BMI), age, very high or low urinary volume, and sodium intake can all influence UFC concentrations and should be taken into account for interpretation.^{29–33} Because urine volume and glomerular filtration rate strongly predict UFC, other screening tests such as LNSC might be preferred for patients with renal impairment (creatinine clearance <60 mL/min) or clinically significant polyuria (>5 L/24 h).^{34,35}

Testing for non-neoplastic hypercortisolism (pseudo-Cushing's syndrome)

Psychiatric disorders, alcohol use disorder, polycystic ovary syndrome, and obesity can activate the hypothalamic–pituitary–adrenal (HPA) axis.^{36,37} Such patients might also have concomitant features of Cushing's syndrome that are common in the general population (eg, weight gain) that lead to biochemical screening. DST, LNSC, and UFC can all show positive (abnormal) results in these patients with non-neoplastic clinical hypercortisolism, or so-called pseudo-Cushing's syndrome.³⁸ Furthermore, concomitant medications could result in steroid cross-reactivity or otherwise interfere with laboratory test results. However, these abnormal results tend to be mildly elevated; UFC is almost always within 3-fold of normal concentrations. The combined LDDT–corticotrophin-releasing hormone (CRH; Dex-CRH) test, LDDT, or the desmopressin test might be able to distinguish between ACTH-dependent Cushing's syndrome and pseudo-Cushing's syndrome.^{39,41} Utility of the Dex-CRH test in this setting is based on the assumption that only patients with ACTH-dependent Cushing's syndrome will show a cortisol response to CRH after dexamethasone suppression.⁴² However, test reliability can differ because of different protocols, use of ovine or human CRH in varying doses, characteristics of cortisol and ACTH assays, and patient characteristics (eg, degree of hypercortisolism, adrenal versus pituitary Cushing's syndrome, and comorbidities). Use of the desmopressin test is based on the finding that ACTH-secreting adenomas express vasopressin V1b receptors (also known as vasopressin 3 receptors), producing an increase in plasma ACTH concentration after desmopressin injection.⁴³ The desmopressin test has a high specificity for Cushing's disease⁴⁴ and is less complex and expensive than the Dex-CRH test, but both tests have shown good diagnostic performance in distinguishing Cushing's syndrome from pseudo-Cushing's syndrome in some studies; when both tests are done, they showed excellent agreement.^{45,46}

Clinical considerations and recommendations for laboratory tests

There is no single preferred diagnostic test for Cushing's syndrome (panel 1), nor is there consensus on how to decide whether and when to test, despite attempts to develop a score for ease of diagnosis.⁴⁷ Clinical judgment

and index of suspicion for Cushing's syndrome are important⁴⁸ and underscore the need to individualise decisions about timing and selection for diagnostic testing on the basis of the clinical scenario (high quality evidence, strong recommendation).

If Cushing's syndrome is suspected, any of the diagnostic tests could be useful. We recommend starting with UFC, LNSC, DST, or a combination (high quality, strong recommendation) depending on local availability; multiple LNSCs might be easier for the patient to complete (high quality, strong recommendation). If an adrenal tumour is suspected, we recommend starting with DST (moderate quality, strong recommendation) and only using LNSC if cortisone concentrations can be also reported^{46,18} (moderate quality, strong recommendation; panel 1).

DST might be the preferred test for shift workers and patients with disrupted circadian rhythm due to uneven sleep schedules, but might not be reliable in women treated with oral oestrogen (high quality, strong recommendation). Measuring dexamethasone levels can be useful if a false-positive DST is suspected due to the clinical scenario (moderate quality, strong recommendation). If UFC is used, two or three collections should be obtained to evaluate variability (high quality, strong recommendation). If LNSC is used, we recommend at least two or three tests (high quality, strong recommendation). Although there were initial concerns about increased risk for infection from SARS-CoV-2 with LNSC,⁴⁹ it remains safe for laboratory personnel when used with proper precautions.⁵⁰ Bilateral inferior petrosal sinus sampling (IPSS) should not be used to diagnose hypercortisolism because the central-to-peripheral ACTH gradient in healthy controls and pseudo-Cushing's syndrome overlaps with that observed in patients with Cushing's disease⁵¹ (high quality, strong recommendation). In classical cyclic Cushing's disease or in patients with unpredictable fluctuating cortisol concentrations, dynamic testing and localisation testing, including IPSS, should be preceded by a confirmatory LNSC or UFC to document that the patients are in the active phase (panel 1).⁵²

Currently, there is no preference for mass spectrometry over immunoassay in measuring cortisol level for diagnosis to ensure that patients with mild hypercortisolism are not excluded.^{18,27} However, normative data with modern assays are needed.

Non-neoplastic hypercortisolism

Non-neoplastic hypercortisolism or pseudo-Cushing's syndrome remains one of the most challenging diagnoses. Because the cause of pseudo-Cushing's syndrome varies, there is no single approach to rule it out.⁵³ We recommend considering the patient's clinical history, particularly the duration of symptoms, and repeating tests to avoid implementing inappropriate treatment if Cushing's syndrome is not present (low quality, discretionary recommendation). In most cases,

patients have mild hypercortisolism and can be monitored for 3–6 months to see whether symptoms resolve; treatment of the underlying condition (such as depression) can restore normal HPA axis function and cortisol concentrations (low quality, discretionary recommendation). Standard diagnostic testing is unreliable in this population. LDDT or serial LNSC tests over time correlate with the clinical picture (low quality, discretionary recommendation). Desmopressin is easy to use and easily administered in an outpatient setting. Dex-CRH in this setting could be valuable, but published diagnostic accuracy results have varied; use at an expert centre with measurement of dexamethasone concentrations is advised (moderate quality, strong recommendation),⁵⁴ as are cortisol cut-off adjustments in patients with severe obesity. CRH is not currently available in the USA, Canada, Brazil, Argentina, Mexico, and some other countries.

Imaging and tumour localisation

MRI is the imaging method of choice for detecting ACTH-secreting pituitary adenomas. However, in part because most lesions are very small, with use of standard 1.5T MRI only approximately 50% of microadenomas are clearly depicted.⁵⁵

Technical refinements, including spoiled gradient-recalled (SPGR) acquisition echo with 1 mm slice intervals, fluid attenuation inversion recovery,⁵⁶ and constructive interference in the steady state, might enhance detection, and variants of T1-weighted turbo spin echo sequences and use of ultra-high-field 3T and 7T magnets allow improved localisation of microadenomas.^{57–60} Nevertheless, approximately a third of scans in patients with Cushing's disease still remain negative,⁶¹ and higher resolution with 3T or 7T magnets can increase the risk of detecting incidentalomas potentially unrelated to the disorder.

Tumour size does not necessarily correlate with degree of hypercortisolism in Cushing's disease. In fact, patients with larger adenomas can present with milder hypercortisolism.⁶²

PET has been explored as an alternative to, or in combination with, MRI for localisation of corticotroph adenomas. ¹⁸F-fluoro-deoxy-glucose (¹⁸F-FDG) PET/CT was largely comparable with standard fast-spin echo MRI in detecting pituitary lesions in one series,⁶³ and a separate study found that both standard-spin echo MRI and high-resolution ¹⁸F-FDG PET were inferior to SPGR MRI.⁶⁴ Prior CRH stimulation can increase ¹⁸F-FDG uptake and thus increase detection.⁶⁵ PET co-registration with volumetric MRI (PET/magnetic resonance coregistration) combines functional and anatomical imaging, and ¹¹C-methionine can permit more accurate localisation of sites of radiotracer uptake.⁶⁶ In one series, this technique correctly localised corticotroph adenomas in patients with de novo disease and persistent or recurrent hypercortisolism after primary surgery, most of whom had negative or equivocal standard-spin echo MRI.⁶⁷

However, this approach is not available or approved in most countries. Alternative strategies (eg, targeting CRH-1 receptors on corticotroph tumours) have also recently been proposed, but require further study.⁶⁸

Clinical considerations and recommendations for imaging and tumour localisation

MRI remains the imaging modality of choice for ACTH-secreting pituitary adenomas (high quality, strong recommendation). We suggest 3T instead of 1.5T MRI where available (low quality, discretionary recommendation). 7T MRI is not widely available and there is currently no justification for re-imaging on 7T MRI if no tumour is detected with 1.5T or 3T MRI.

It is likely that functional imaging will ultimately prove to be a better approach than MRI alone. However, more data are needed to define use of different ligands in various clinical settings. Although advanced imaging technologies are available in some centres of excellence, the benefit of referring all patients for further imaging after 3T MRI remains unknown.

Distinguishing between Cushing's disease and ectopic ACTH-dependent Cushing's syndrome

In patients with Cushing's disease, glucocorticoid receptors typically retain the ability to inhibit ACTH secretion in the presence of high dexamethasone doses, and vasopressin V2 and V1b (V3) receptors, along with CRH receptor, are all overexpressed. By contrast, most (but not all) ectopic ACTH-secreting tumours do not express these receptors. Accordingly, desmopressin and CRH stimulation testing have proven useful in distinguishing between pituitary and ectopic tumours.^{69–71} Increased plasma ACTH and increased cortisol concentrations after CRH or desmopressin administration usually indicates Cushing's disease.^{72–76} Using more than one dynamic test might further improve clinical accuracy.⁷⁷ Nevertheless, well differentiated neuroendocrine tumours can also express any or all of these receptors, potentially leading to false-positive results. High-dose (8 mg) DST, although it has low accuracy overall, is still used in some countries. None of the diagnostic tests have 100% specificity and results can be discordant in up to a third of patients;^{5,6} differences in type of ectopic tumour, as well as patient age, sex, and severity of hypercortisolism can all influence outcomes.

IPSS, which measures ACTH in pituitary versus peripheral venous drainage, has long been the gold standard to reliably exclude ectopic ACTH production^{78,79} and should preferably be performed in a specialised centre because of potential patient risk. A central-to-peripheral ACTH gradient less than 2 before or less than 3 after stimulation suggests an ectopic tumour; however, both false-negatives and false-positives have been reported. Prolactin measurement might improve diagnostic accuracy and it is essential that the patient is hypercortisolaemic at the time of IPSS.⁸⁰

A non-invasive approach using a combination of three or four tests, specifically CRH and desmopressin stimulation plus MRI, followed by whole-body CT if diagnosis is equivocal, correctly diagnosed Cushing's disease in approximately half of patients in one series, potentially eliminating the need for IPSS.⁸¹ A positive CT scan, negative CRH and desmopressin stimulation, and negative MRI, had a negative predictive value of 100% for Cushing's disease. Currently, this combination of laboratory and imaging testing as a non-invasive approach to distinguish between pituitary and ectopic ACTH-secreting tumours is likely to be limited to specialised centres.⁸²

⁶⁸Ga-DOTATATE is a modified (Tyr3)-octreotide molecule covalently linked to 1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid (DOTA) combined with the radioactive ⁶⁸Ga isotope. The radiopharmaceutical, with a half-life of approximately 1 h, binds to somatostatin receptors with affinity similar to octreotide and can be used as a tracer in PET imaging of ectopic ACTH-secreting neuroendocrine tumours.⁸³ ⁶⁸Ga-DOTATATE localises about 65% of these tumours,⁸⁴ including those not seen or not definitively identified on cross-sectional imaging, and images are sharper than with single photon ¹¹¹In-DTPA-pentetreotide, with greater sensitivity for small tumours.^{85,86} False-positives can occur because of chronic inflammation, and a positive scan does not definitively prove that the neuroendocrine tumour is the source of ACTH, but ⁶⁸Ga-DOTATATE imaging can be useful in guiding clinical management.⁸⁷

The ⁶⁸Ga isotope is typically derived from decaying ⁶⁸Ge and the worldwide supply of ⁶⁸Ge is being exhausted. The ⁶⁸Ga isotope, if it can be generated locally via a cyclotron, or ⁶⁴Cu, which has a longer 12.7-h half-life and can be centrally produced, could be used as alternative DOTATATE, DOTATOC, or DOTANOC conjugates.⁸⁸

Clinical considerations and recommendations for distinguishing between Cushing's disease and ectopic ACTH-dependent Cushing's syndrome

No single laboratory test or combination of tests can absolutely differentiate between pituitary and ectopic ACTH-secreting tumours (high quality, strong recommendation). We recommend using both the clinical context and test results to guide management (high quality, strong recommendation). When prompt access to brain MRI is not available, neck-to-pelvis thin-slice CT scan is useful if suspicion is high for ectopic ACTH syndrome, such as in a male patient with very high UFC, profound hypokalaemia, or both⁸¹ (low quality, discretionary recommendation).

If a pituitary tumour with a diameter of 10 mm or larger is detected on MRI and dynamic testing results are consistent with Cushing's disease, IPSS is not necessary for diagnosis (moderate quality, strong recommendation). As it is possible that a pituitary lesion detected on MRI is an incidental nonfunctioning adenoma or other sellar mass and the ACTH source is ectopic, clinical presentation should always be considered. Some studies suggest this is

true for lesions larger than 6 mm, but not all expert centres use this lower cutoff. There was consensus that all patients with lesions less than 6 mm should have IPSS and those with lesions of 10 mm or larger do not need IPSS (moderate quality, strong recommendation). Expert opinions differ regarding tumors 6–9 mm, but the majority recommended IPSS to confirm the diagnosis in this circumstance (moderate quality, discretionary recommendation). Notably, some differences between centres and countries are based on interventional radiology availability. Prolactin measurement can be useful in ruling out a false-negative IPSS (moderate quality, discretionary recommendation). Although IPSS has high diagnostic accuracy for localisation to the pituitary gland, it is not sufficiently reliable for tumour lateralisation to the right or left side of the gland (moderate quality, strong recommendation).

A non-invasive alternative using high-dose DST and CRH stimulation test predicts Cushing's disease if both tests are positive.⁸⁹ However, if tests are discordant, IPSS is necessary (low quality, discretionary recommendation). Emerging data suggest that CRH and desmopressin testing with pituitary MRI followed by whole-body CT scan might be a reliable alternative, if assessed by an experienced multidisciplinary team (very low quality, discretionary recommendation).

Complications of Cushing's disease

Strategies for Cushing's disease management should consider how comorbidities and complications associated with Cushing's disease might compromise patient health and quality of life. Comorbidities should be addressed in many cases concomitant with or even before Cushing's disease-specific treatments to restore normal cortisol levels. Clinical considerations and recommendations regarding complications of Cushing's disease are summarised in panel 2.

Hypercoagulability

Hypercoagulability in Cushing's syndrome resulting in increased risk of thromboembolic events is paradoxically coupled with an increased bleeding tendency due to skin atrophy and capillary fragility.^{90,91} Most patients show an activated coagulation cascade, including shortened activated partial thromboplastin time and increased fibrinogen, von Willebrand factor, and factor VIII, as well as impaired fibrinolysis mediated by elevated plasminogen activator inhibitor-1 and antiplasmin concentrations. Increased thrombin, thromboxane A2, and platelets, with a compensatory increase in anti-coagulation factors such as vitamin K-dependent protein C and vitamin K-dependent protein S, have also been implicated in hypercoagulability.^{92,93}

The incidence of venous thromboembolic events (VTE) in patients with endogenous Cushing's syndrome is more than ten times higher versus those with nonfunctioning pituitary adenomas undergoing surgery⁹⁴ with an odds ratio (OR) of 17.82 (95% CI 15.24–20.85) compared with

Panel 2: Recommendations regarding complications of Cushing's disease

Hypercoagulability

- There is currently no standard practice for preoperative or postoperative thromboprophylaxis in patients with Cushing's disease. Some experts pause oestrogen therapy in women who are awaiting surgery, but care should be taken if it was being used as contraception, because pregnancy also is associated with increased risk of thrombosis (low quality, discretionary recommendation)
- Prophylactic anticoagulation should be considered for patients at risk for venous thromboembolic events, including history of embolism or abnormal coagulation testing; severe preoperative hypercortisolism; current use of oestrogen or oral contraceptives; poor mobility; extended preoperative or postoperative hospital stay; and high postoperative cortisol concentrations or cortisol over-replacement in patients with adrenal insufficiency (moderate quality, strong recommendation)
- Early postoperative ambulation and use of compression stockings should be encouraged for all patients (high quality, strong recommendation)
- If thromboprophylaxis is administered, there was strong consensus for preference of low molecular weight heparin over oral anticoagulants given the long half-life of the latter and the absence of therapy to reverse their effect, which could be especially concerning in the preoperative setting (low quality, discretionary recommendation)
- Anticoagulants could be discontinued before surgery to minimise intraoperative bleeding risk, although the timing of when to stop and when to reinstate after surgery is unclear (low quality, discretionary recommendation)
- Among meeting participants, recommended anticoagulation duration in the preoperative setting ranged from 2–4 days to 1–2 weeks, and in the postoperative setting from 1–2 days of the hospital stay up to 2–4 weeks, or even longer, to 2–3 months (low quality, discretionary recommendation)
- Thromboprophylaxis should not be routinely used in paediatric patients because of bleeding risk but is reserved for selected patients

Cardiovascular disease

- Evaluate, monitor, and treat according to current guidelines for patients at high risk of cardiovascular disease (high quality, strong recommendation)
- Management approach should be individualised (high quality, strong recommendation) on the basis of the complications present (eg, hypertension or hyperlipidaemia) and care should be coordinated with primary care and cardiology physicians as needed (very low quality, discretionary recommendation)

Bone disease

- Risk assessment for bone loss and fracture recommended in all patients (high quality, strong recommendation)

- Given the risk for fracture even in patients without osteoporosis, standard dual X-ray absorptiometry alone may not be sufficiently informative; bone quality (microscanner or trabecular bone score) or morphometric vertebral assessment is recommended where available (high quality, strong recommendation) and can be useful in detecting subclinical fractures (high quality, strong recommendation), but might not be practical for all patients. The FRAX tool to assess fracture risk is not validated for Cushing's disease
- Monitor and follow-up as for all adult high-risk populations (high quality, strong recommendation)
- Consider conventional osteoporosis treatments (eg, bisphosphonates) for patients with persistent Cushing's disease, even if bone mineral density is normal, because of increased fracture risk due to cortisol excess (high quality, strong recommendation)

Growth hormone deficiency

- There is currently no standard practice for whether, when, and how to test for growth hormone deficiency in adults with Cushing's disease. As postoperative hypothalamic–pituitary–adrenal (HPA) axis recovery is often delayed, we recommend waiting at least 6–12 months after surgery before considering growth hormone deficiency assessment (moderate quality, strong recommendation)
- Patients with macroadenomas and more aggressive surgical resection are at increased risk of hypopituitarism; patients with three or more pituitary hormone deficiencies are more likely to have growth hormone deficiency and do not need dynamic testing (high quality, strong recommendation)
- Serum insulin-like growth factor I concentration alone is not likely to be a reliable indicator of growth hormone deficiency, because concentrations can be in the lower half of the normal range.
- Accessibility of growth hormone replacement can be an important factor in determining testing and treatment considerations. If growth hormone replacement is implemented earlier than 2 years after pituitary surgery, we recommend retesting periodically to determine whether growth hormone secretion has normalised upon HPA axis recovery (moderate quality, strong recommendation)
- As Cushing's syndrome-associated myopathy does not always spontaneously resolve during remission, physical rehabilitation is recommended for all patients (low quality, discretionary recommendation).
- In children, evaluate for growth hormone deficiency 3–6 months after surgery and immediately initiate growth hormone replacement if needed to ensure proper growth

the healthy population.⁹² VTE risk persists in the first few months after Cushing's disease surgery, indicating that hypercoagulability is not immediately reversible with cortisol normalisation.^{92,95,96} At 30 days after adrenalectomy, VTE risk was 3·4–4·75%,⁹⁶ and the OR for thromboembolic events after bilateral adrenalectomy in a longer-term study was 3·74 (95% CI 1·69–8·27).⁹⁵ In a series of 17 patients, biochemical remission following short-term medical therapy (with various combinations of pasireotide, cabergoline, and ketoconazole) also did not seem to reverse the risk or induce changes in pro-anticoagulation factors; pulmonary embolism occurred in two patients with a marked UFC decrease.^{90,97}

Data from retrospective studies^{98,99} indicate that thromboprophylaxis can decrease the incidence of postoperative VTE, particularly when extended to 30 days. Surveys indicate increased awareness of the need for thromboprophylaxis and increased anticoagulation use in clinical practice,¹⁰⁰ but strategies to identify patients most likely to benefit are still being developed.¹⁰¹

Cardiovascular disease

Patients with Cushing's disease show an adverse cardiovascular disease risk profile that may persist even after successful treatment.^{102–105} Visceral, subcutaneous, and total fat can decrease after remission, although most patients remain with overweight or obesity.¹⁰⁶ Type 2 diabetes is present in up to 30% of patients and dyslipidaemia, and low HDL, high LDL, and high triglycerides were reported in 16–64% of cases at diagnosis. In many patients, but not all, type 2 diabetes resolves after remission.¹⁰⁷ Structural cardiovascular changes improve, including left ventricular hypertrophy, concentric remodeling, dilated cardiomyopathy, increased intima media thickness, and increased formation of atherosclerotic plaques, as well as their clinical manifestations, including hypertension and heart failure, but might not fully resolve despite remission of hypercortisolism.¹⁰⁸

Myocardial infarction, stroke,^{109,110} and other vascular events are a primary cause of increased standardised mortality ratio (4·1–16·0) in patients with active or persistent Cushing's disease.¹¹¹ Most studies show these rates do not entirely normalise,^{110,112} but are lowered upon remission, and in one study, patients in remission after a single pituitary surgery had a normal standardised mortality ratio at 10 years.¹¹³ Screening and risk assessment for cardiovascular risk factors before and after surgery is therefore essential.¹¹⁴

Bone disease

Skeletal fragility is a frequent and early complication of hypercortisolism, and fractures could be the first clinical manifestation of the disease. Vertebral fractures occur in 30–50% of patients, largely correlating with hypercortisolism severity.¹¹⁵ Suppression of the growth hormone–insulin-like growth factor I (GH–IGF-I) and hypothalamic–pituitary–gonadal axes, as well as altered

parathyroid hormone pulsatility, lead to decreased osteoblast number and function, as evidenced by decreased serum concentrations of bone formation markers including osteocalcin and alkaline phosphatase.¹¹⁶ Dual X-ray absorptiometry of the lumbar spine might show low bone mineral density (BMD), but fractures can occur even in patients with BMD in the normal or osteopenic range.¹¹⁷ Although BMD increases are reported after hypercortisolism resolution, some patients show persistently high fracture risk, with men at higher risk than women. Conventional osteoporosis treatments, such as bisphosphonates, as well as supportive treatment with vitamin D and calcium, can induce a more rapid improvement in BMD than cortisol normalisation alone, and could be useful in patients with persistent postsurgical hypercortisolism to prevent further bone loss.¹¹⁸ Data about the role of specific bone treatments for patients with osteopenia who are in remission after Cushing's disease treatment are scarce.

Growth hormone deficiency

Glucocorticoids, both endogenous and exogenous, inhibit growth hormone secretion, thereby decreasing IGF-I production by the liver in patients with Cushing's syndrome.^{119,120} Although growth hormone production can be fully restored in most patients after successful therapy and recovery of the HPA axis, even years after remission,¹²¹ persistence of growth hormone deficiency can potentially worsen hypercortisolism complications such as bone loss, myopathy, and memory deficits.¹²² Using the insulin tolerance or glucagon stimulation test, prevalence of growth hormone deficiency in adults varies with timing of the diagnosis, ranging from 50–60% when testing was done within 2 years after surgery to 8–13% when done more than 2 years after surgery.^{121,123} A prevalence rate of 65% was observed with the GHRH-arginine test after a median remission time of 3 years after surgery,¹²⁴ whereas 36% of patients were diagnosed with growth hormone deficiency at 99 months after remission post-radiotherapy.¹²³ Prevalence using the macimorelin stimulation test is not known.¹²⁰ Notably, IGF-I is an insensitive screening test for diagnosing growth hormone deficiency in adults.¹²⁴

Compared with other causes of growth hormone deficiency, growth hormone deficiency in patients with Cushing's syndrome is more common in women and young patients; generally, these patients have a higher prevalence of type 2 diabetes, hypertension, low bone mass, fractures, and worse quality of life.^{125–127} Myopathy might be partially related to growth hormone deficiency among patients in remission. Although preoperative IGF-I concentrations during active Cushing's syndrome did not predict long-term myopathy risk, low 6-month postoperative IGF-I concentrations strongly predicted more severe long-term muscle atrophy and weakness after Cushing's syndrome remission.¹²⁸

Growth hormone replacement ameliorates several complications associated with metabolic syndrome and

risk for cardiovascular and cerebrovascular disease. Studies show decreased bodyweight, waist circumference, and total and LDL-cholesterol, as well as quality of life and BMD improvement. Conversely, in patients with pre-existing glucose intolerance, replacement can worsen glucose metabolism.^{125–127,129–131} Growth hormone replacement has not yet been shown in randomised, prospective trials to reverse metabolic syndrome and cardiovascular or cerebrovascular complications.¹²⁶

Other complications

Increased risk of infection,¹¹⁴ dysfunction of one or more pituitary axes such as central hypothyroidism,¹³² gonadal function impairment, infertility, and other complications can be seen in patients with Cushing's disease. Physical and psychological morbidity commonly affects quality of life, even after successful treatment in some patients. Persistence of several features associated with prior hypercortisolism, including affective disorders, cognitive dysfunction, and negative illness perception can have a sustained effect on patients' wellbeing.¹³³ Proximal myopathy is characteristic of Cushing's syndrome and may persist despite biochemical remission.^{134,135} The pathology is multifactorial, including protein degradation through the forkhead box O3 pathway, as well as accumulation of intramuscular fat and inactivity-associated muscle atrophy.¹³⁵ Furthermore, hypercortisolism remission can induce exacerbation of pre-existing autoimmune disorders.

Because these complications have been the subject of recent guidelines¹³⁶ and reviews,^{102,134} they were not specifically addressed at the workshop.

Initial treatment of Cushing's disease and monitoring for recurrence

Pituitary surgery

Transsphenoidal surgery is recommended as first-line therapy for patients with Cushing's disease.^{6,7} Remission, typically defined as postoperative serum cortisol concentrations lower than 55 nmol/L (<2 µg/dL), is seen in approximately 80% of patients with microadenomas and 60% with macroadenomas if the procedure is performed by an experienced surgeon.^{137–140} Patients in remission require glucocorticoid replacement until HPA axis recovery.^{7,136} As remission could be delayed, monitoring until postoperative cortisol nadir can usually identify such cases.^{141,142} Occasionally, patients with mild hypercortisolism, cyclic Cushing's disease, or those treated medically before surgery can achieve remission without marked postoperative hypocortisolism. Treatment at a high-volume centre by an experienced surgeon and tumour characteristics such as detection on MRI, noninvasiveness, and size smaller than 10 mm appear to correlate with increased remission rates,^{138,143} whether there is a potential incremental benefit with an endoscopic approach for macroadenomas remains unclear.^{144,145} Overall,

complication rates are low, with more experienced surgeons having even lower rates than less experienced surgeons.^{146,147} New-onset hypopituitarism (in approximately 10% of patients), as well as permanent diabetes insipidus, CSF leak, and VTE (in <5% of patients), are the most common complications; peri-operative mortality is <1%.^{143,144}

How to measure surgical expertise for Cushing's disease remains unclear. Hospitals that limit the number of neurosurgeons performing transsphenoidal surgery and therefore increase surgeon experience show better outcomes and fewer complications, compared with other hospitals, as well as shorter postoperative length of stay, and lower costs. Among neurosurgeons who perform transsphenoidal surgery, survey data demonstrate that those who have done more than 200 transsphenoidal surgeries have the lowest complication rates.^{148–151} Regionalised neurosurgery teams of four or five experts per 2·5–5 million inhabitants could potentially allow for optimal outcomes, reduced costs, and increased quality of care overall.^{149,152}

Clinical considerations and recommendations for pituitary surgery

We recommend patients with Cushing's disease undergo surgery in specialised pituitary tumour centres of excellence wherever possible (high quality, strong recommendation).¹⁵² Surgery should be done by an experienced pituitary neurosurgeon with follow-up by a multidisciplinary team including a pituitary endocrinologist (high quality, strong recommendation). Outcomes of pituitary surgery and cost-effectiveness (low quality, discretionary recommendation) should be reported and be made publicly available.

Monitoring for recurrence

Recurrence after successful pituitary surgery is characterised as the reappearance of clinical and biochemical features of hypercortisolism after initial remission. Low or undetectable cortisol concentrations in the immediate postoperative period is a defining criterion of remission, but does not necessarily predict lack of recurrence;¹⁵³ some patients who show early remission with very low (<2–5 µg/dL) postoperative cortisol concentrations might experience recurrence later.¹⁵⁴ Published recurrence rates vary between 5% and 35%, with half of recurrences appearing within the first 5 years after surgery and half after up to 10 years or more.^{137,155–157}

Lifelong monitoring for recurrence is required (panel 1).¹⁵⁸ In patients who responded preoperatively to desmopressin, early postoperative loss of response to desmopressin with or without dexamethasone or CRH could predict recurrence risk,^{70,159–165} but is not consistently used or recommended by most experts.

Compared with use in the initial diagnosis of Cushing's syndrome, LNSC, 1-mg DST, UFC, and desmopressin

| | Cutoff* | Sensitivity (%) | Specificity (%) | Advantages and instructions for testing | Disadvantages and pitfalls |
|-------------------------------------|--|-----------------|-----------------|--|---|
| Diagnosis | | | | | |
| 1 mg dexamethasone suppression test | 1.8 µg/dL (50 nmol/L) | 98 | 81 | High negative predictive value; easy for health-care provider to administer | False positives common; variable dexamethasone metabolism can confound results; oral oestrogen can increase corticosteroid-binding globulin |
| 24-h urinary-free cortisol | Assay-specific reference range | 91 | 81.5 | Wide range for normal values | Cumbersome for patient to undertake; variability could be 50% between samples, thus 2–3 collections are needed |
| Late-night salivary cortisol | Assay-specific reference range | 97 | 97.5 | Easy for patient to perform; patients should be cautioned not to eat, drink, smoke, or brush their teeth for 15 min before collecting saliva samples | Intra-patient variability; cut-offs vary substantially based on reference laboratory; potential for contamination with topical hydrocortisone; not available in all centres |
| Monitoring for recurrence | | | | | |
| Late-night salivary cortisol | 0.27 µg/dL (7.5 nmol/L) | 75–90 | 93–95 | In most patients late-night salivary cortisol is abnormal earlier than dexamethasone suppression test and urinary-free cortisol | Intra-patient variability; can be normal despite recurrence |
| 24-h urinary-free cortisol | 1.6 × ULN | 68 | 100 | Direct reflection of bioavailable cortisol | Approximately 50% intra-patient variability; last test to show abnormal results |
| Desmopressin test | Absolute cortisol increments of 7.0–7.4 µg/dL from baseline† | 68 | 95 | Earliest test to show positive results in some studies; predicts presence of corticotroph tumour; can become positive before clinical adenoma recurrence | Dynamic labour-intensive testing |
| 1 mg dexamethasone suppression test | 1.8 µg/dL (50 nmol/L) | NA | NA | Likely to be abnormal before 24-h urinary-free cortisol | Limited evidence specifically assessing utility for recurrence |

ULN=upper level of normal. NA=not available. ACTH=adrenocorticotropic hormone.*Cutoffs specified are for adults. Some experts recommend using the same cutoffs for initial diagnosis and recurrence. †Some studies use ACTH absolute cutoffs or increments.

Table 1: Laboratory tests for Cushing's syndrome diagnosis and monitoring for Cushing's disease recurrence^{12,13,158,166}

tests have a lower sensitivity for recurrence, but specificity is high (table 1).¹⁵⁸ LNSC can detect postoperative elevated cortisol concentrations earlier than 1-mg DST, and UFC is usually the last test to show abnormal findings in patients who recur.^{166,167} Thus, LNSC could allow for earlier intervention, but serial tests are advised due to wide variability in results.^{167–170}

Evaluation for recurrence should begin after HPA axis recovery, and then annually or sooner if there is clinical suspicion.^{171,172} In practice, however, clinical manifestations and biomarkers can be discordant. Moreover, diagnosis of early recurrence presents the additional challenge about when and how to intervene with treatment.^{171,172}

Clinical considerations and recommendations for monitoring recurrence

We recommend lifelong monitoring for recurrence of Cushing's disease (moderate quality, strong recommendation). Postoperative dynamic testing can potentially predict recurrence (low quality, discretionary recommendation), but its utility in clinical practice remains to be established as some patients with low predicted likelihood of recurrence can recur many years later.

Among the tests available, LNSC is the most sensitive for detecting recurrence and should be done annually after HPA axis recovery postoperatively (moderate quality, strong recommendation). LNSC usually shows abnormal results before DST and UFC,^{166,167} although monitoring for recurrence should also take into consideration which specific tests showed abnormal

result for an individual patient at initial diagnosis (moderate quality, strong recommendation). If only slight biochemical abnormalities are seen without clinical features of hypercortisolism, close monitoring with repeat testing and treatment of comorbidities rather than treatment of the underlying disorder can be considered (low quality, discretionary recommendation).

Repeat pituitary surgery

Repeat transsphenoidal surgery can be considered in patients with biochemical evidence of recurrent Cushing's disease with visible tumour on MRI.^{139,173–176} At selected expert centres where successful reoperation has been reported despite the absence of detectable adenoma on MRI, either ACTH-staining adenoma on pathology or a central ACTH gradient on IPSS at initial operation was often present.^{174,175}

Tumour factors, including size and presence of extrasellar extension, should be considered regarding eligibility for reoperation, and neurosurgeon experience probably plays a role in achieving good results.^{155,156,177} Remission rates after reoperation vary widely in the literature, ranging from 37% to 88%, at least in part because of different remission criteria and follow-up duration.¹⁷⁴ Although some studies have reported a substantially higher incidence of both surgical (eg, CSF leak, meningitis) and endocrinological complications (eg, diabetes insipidus and hypopituitarism) with repeat versus initial surgery, serious morbidity is less likely in experienced hands.^{155,156}

Clinical considerations and recommendations for repeat pituitary surgery

If there are no contraindications for surgery, we suggest repeat transsphenoidal surgery in patients with

biochemical evidence of recurrent Cushing's disease if tumour is evident on MRI, especially if the first surgery was not done in a pituitary tumour centre of excellence (low quality, discretionary recommendation). If MRI

| | Commonly used doses | Efficacy | Adverse effects | Key considerations |
|---|--|--|---|---|
| Adrenal steroidogenesis inhibitor | | | | |
| Ketoconazole ^{179,181-187} | 400–1600 mg total per day, orally, given twice or three times a day | Retrospective studies: approximately 65% of patients had UFC normalisation initially, but 15–25% escape | Gastrointestinal disturbances, increased liver enzymes, gynecomastia, skin rash, adrenal insufficiency | EMA-approved for treatment of endogenous Cushing's syndrome, off-label use in USA; increasing doses may be needed to counter escape; needs gastric acid for absorption (avoid proton-pump inhibitors); decrease in testosterone would be preferred in women, men need follow-up for hypogonadism; risk of serious hepatotoxicity, mostly transient but regular liver function test monitoring required; risk of QTc prolongation; careful review of other medications for potential drug–drug interactions is essential |
| Osilodrostat ^{181-183,188-192} | 4–14 mg total per day, orally, given twice a day as maintenance dose; some patients require lower starting doses at 2 mg per day; 30 mg, twice a day maximum | Phase 3 randomised withdrawal study showed 86% UFC normalisation | Increased androgenic and mineralocorticoid precursors (hirsutism, hypertension, hypokalaemia), gastrointestinal disturbances, asthenia, adrenal insufficiency | FDA-approved for patients with Cushing's disease in whom pituitary surgery is not an option or has not been curative; EMA and Japan have approved for treatment of endogenous Cushing's syndrome; not yet widely available; rapid decrease in UFC; risk of hypocortisolism, hypokalaemia, and QTc prolongation; 11-deoxycortisol can cross-react in cortisol immunoassays; careful monitoring for hyperandrogenism in women |
| Metyrapone ^{179,181,182,193-197} | 500 mg to 6 g total per day, orally, given three or four times a day | UFC normalisation in retrospective studies approximately 70%; in a prospective study, 47% at week 12 | Increased androgenic and mineralocorticoid precursors (hirsutism, hypertension, hypokalaemia), gastrointestinal disturbances, adrenal insufficiency | EMA-approved for treatment of endogenous Cushing's syndrome, off-label use in USA; rapid decrease in UFC, typically in first month; 11-deoxycortisol can cross-react in cortisol immunoassays; hyperandrogenism needs to be monitored with long-term use in women |
| Mitotane ^{179,181,182,198} | 500 mg to 4 g total per day, orally, up to 5 g in Cushing's disease per day given three times a day | Retrospective studies show approximately 80% UFC normalisation | Gastrointestinal disturbances, dizziness, cognitive alterations, adrenal insufficiency; increased liver enzymes; treatment should be stopped if elevations are >5 × ULN | Approved by the FDA and EMA for treatment of adrenal cancer with endogenous Cushing's syndrome; slow onset of action, highly variable bioavailability; narrow therapeutic window (dose titration based on mitotane plasma concentrations); 11-deoxycortisol can cross-react in cortisol immunoassays; neurological toxicity could be a limiting factor; teratogenicity and abortifacient activity, coupled with a long half-life, could limit use in women who desire future pregnancy |
| Etomidate ^{179,199-201} | 0.04–0.1 mg/kg/h intravenously for patients in the intensive care unit; 0.025 mg/kg/h for patients not in the intensive care unit | Retrospective studies show approximately 100% serum cortisol control (10–20 µg/dL) | Sedation or anaesthesia; adrenal insufficiency, myoclonus, nausea, vomiting, and dystonic reactions at higher anaesthetic doses | Off-label use only; very rapid onset of action, appropriate for acute treatment of severe hypercortisolism; intravenous hydrocortisone required at high doses to avoid adrenal insufficiency |
| Levoketoconazole ^{*202,203} | 300–1200 mg total per day, orally, given twice a day | Phase 3 open label study showed 31% UFC normalisation (primary endpoint), 42% normalisation when using imputed data (comparable with other studies); phase 3 randomised withdrawal study showed that 41% lost response with drug vs 96% with placebo; clinical signs and symptoms of hypercortisolism improved | Gastrointestinal disturbances, headache, oedema, increased liver enzymes, adrenal insufficiency | Investigational; FDA and EMA orphan drug status for treatment of endogenous Cushing's syndrome; possible lower risk for hepatotoxicity than with ketoconazole based on animal models, although no head-to-head studies in humans available; needs gastric acid for absorption (avoid proton-pump inhibitors); risk of QTc prolongation; careful review of other medications for potential drug–drug interactions is essential |
| Somatostatin receptor ligands | | | | |
| Pasireotide ^{e179,182,204-206} | 0.6–1.8 mg/mL subcutaneously total per day, given twice a day | Phase 3 study showed 15–26% UFC normalisation | Hyperglycaemia, type 2 diabetes, diarrhoea, nausea, abdominal pain, cholelithiasis, fatigue | Widely approved for patients with Cushing's disease in whom pituitary surgery is not an option or has not been curative; may decrease tumour volume; high risk of hyperglycaemia requires careful patient selection; risk of QTc prolongation |
| Pasireotide long-acting release ^{e181,207-209} | 10–30 mg per month, intramuscularly | Phase 3 study showed 40% UFC normalisation; clinical signs and symptoms of hypercortisolism improved | Hyperglycaemia, type 2 diabetes, diarrhoea, nausea, abdominal pain, cholelithiasis, fatigue | Widely approved for patients with Cushing's disease in whom pituitary surgery is not an option or has not been curative; decreases tumour volume; high risk of hyperglycaemia requires careful patient selection; risk of QTc prolongation |

(Table 2 continues on next page)

| Commonly used doses | Efficacy | Adverse effects | Key considerations |
|---|--|---|---|
| (Continued from previous page) | | | |
| Dopamine receptor agonists | | | |
| Cabergoline ^{179,187,210-214} | 0.5–7 mg total per week, orally | Retrospective studies showed approximately 40% UFC normalisation initially, but roughly 25–40% escape; clinical signs and symptoms of hypercortisolism improved | Headache, nasal congestion, hypotension, depression, dizziness |
| Glucocorticoid receptor blocker | | | |
| Mifepristone ^{179,187,215-218} | 300–1200 mg total per day orally, given once a day | Open-label phase 3 study showed significant improvement in glycaemia (approximately 60% of patients) and blood pressure; clinical signs and symptoms of hypercortisolism improved | Gastrointestinal disturbances, headache, hypokalaemia, arthralgia, peripheral oedema, hypertension, vaginal bleeding, adrenal insufficiency |
| EMA=European Medicines Agency. FDA=US Food and Drug Administration. ULN=upper limit of normal. UFC=urinary-free cortisol. *Investigational drug with completed phase 3 clinical trials. | | | |
| Table 2: Summary of medical therapies for Cushing's disease | | | |

does not show tumour presence, reoperation might be appropriate if an experienced surgeon at a high-volume centre considers it feasible and positive pathology or a central gradient on IPSS was seen before the initial operation (low quality, discretionary recommendation).

Medical therapy for Cushing's disease

Drugs used for treatment of Cushing's disease target adrenal steroidogenesis, somatostatin and dopamine receptors in the pituitary gland, and glucocorticoid receptors.^{6,7,178} Drugs can be used to treat hypercortisolism in patients with persistent or recurrent Cushing's disease and those who are not candidates or refuse surgery, and to control cortisol concentrations in patients undergoing radiotherapy.^{139,179,180} Available medications and investigational drugs that have reported phase 3 trial results are described in table 2.

Targeting adrenal steroidogenesis

Adrenal steroidogenesis inhibitors that have been available for many years, including ketoconazole, metyrapone, mitotane, and etomidate, as well as the recently approved osilodrostat, block one or more adrenal enzymes, decreasing glucocorticoid synthesis or adrenal androgen production and secretion, or both.¹⁸¹ They are effective in controlling cortisol excess, but do not directly target the pituitary ACTH-secreting adenoma, nor do they restore HPA-axis circadian rhythm.¹⁸²

When treatment is dose-titrated to achieve cortisol normalisation, there is a risk of adrenal insufficiency with overtreatment. Alternatively, for patients treated from the start with high doses of adrenal steroidogenesis inhibitors to block endogenous cortisol secretion and with exogenous glucocorticoid replacement to avoid adrenal insufficiency (ie, a block-and-replace regimen), there is a risk of inappropriate glucocorticoid over-replacement if blockade is incomplete.¹⁸⁰ Some adverse events relate to ACTH

increase in patients with Cushing's disease and buildup of adrenal hormones proximal to the blockade with mineralocorticoid or androgenic activity. Potential adverse events related to drug–drug interactions are a key factor in treatment selection and use.¹⁸³

Ketoconazole

Ketoconazole blocks multiple adrenal enzymes, including those involved early in the steroid biosynthetic pathway. This approach avoids excess circulation of androgen and mineralocorticoid precursors, but it can also decrease gonadal steroid synthesis; men might experience hypogonadism and gynaecomastia, which can limit prolonged treatment.¹⁸⁴ A review of 310 patients with Cushing's syndrome treated in five studies with a mean dose of 673.9 mg per day of ketoconazole and followed for a mean of 12.6 months showed UFC normalisation in 64.3% of patients (median 50%, range 44.7–92.9%), but up to 23% of initially responsive patients lost biochemical control.¹⁷⁹ Similarly, data derived from the largest retrospective study of 200 patients with Cushing's disease who took ketoconazole showed that 33 (64.7%) of 51 patients treated for more than 24 months with a mean dose of 600 mg per day normalised UFC concentrations, but 15.4% escaped.¹⁸⁵ Improvement in clinical features of Cushing's syndrome has also been observed, including decreased bodyweight and blood pressure, improved glucose metabolism, and decreased muscle weakness.¹⁷⁹

Hepatotoxicity (10–20% of patients) is mostly asymptomatic with mild or moderate increases in liver enzymes ($\leq 5 \times \text{ULN}$),¹⁸⁶ and typically appears within the first 6 months of treatment; these increases seem not to be dose-dependent and reverse within 2–12 weeks after dose decrease or discontinuation. However, because serious hepatotoxicity has been reported in patients without obvious risk factors, the United States Food and Drug Administration (FDA) introduced a black-box

warning and recommends weekly monitoring of liver function tests in patients with fungal infections treated with ketoconazole. Of note, ketoconazole use for Cushing's syndrome is off-label in the USA. Gastrointestinal disturbances and adrenal insufficiency are also common, seen in 5–20% of patients, and skin rash is observed in approximately 5%.¹⁷⁹ There are several drug–drug interactions with ketoconazole; careful review of the patient's medication list for potentially problematic interactions is essential.

Metyrapone

Treatment with the 11 β -hydroxylase inhibitor metyrapone in 120 patients with Cushing's syndrome (five studies; mean dose 2127.5 mg per day, mean follow-up 8.7 months) showed UFC normalisation in 71% (median 75.5%; range 45.4–100%), with up to 18% escaping after initial response.¹⁷⁹ A subsequent retrospective multicentre study of 164 patients with Cushing's syndrome reported that 43% achieved biochemical control with UFC, with a mean of 8 months monotherapy, at a mean starting dose of 1040 mg per day and escalating to 1425 mg per day.¹⁹³ An observational study of 31 patients with Cushing's syndrome, including 20 with Cushing's disease, showed that a median dose of 1000 mg per day for 9 months induced a rapid decrease from baseline in both UFC (–67%) and LNSC (–57%) after the first month of treatment, with sustained normalisation in UFC in 70% of patients and in LNSC in 37% of patients at last visit.¹⁹⁴ Three patients had loss of control at 9 months despite normal UFC concentrations at 6 months and two patients also showed normal LNSC. Notably, 11-deoxycortisol might produce clinically relevant cross-reactivity with cortisol in both blood and urine immunoassays.¹⁹⁵ A multicentre prospective study of 50 patients with Cushing's syndrome showed that 23 (47%) had UFC normalisation at 12 weeks (final median metyrapone dose at week 12 was 1500 mg [250; 5500] mg per day) and adrenal insufficiency was reported in 6 (12%) of patients.¹⁹⁶

Patients treated with metyrapone typically show a general improvement in clinical features of Cushing's syndrome (66% in the prospective study), such as blood pressure, glucose metabolism, psychiatric disturbances, and muscle weakness.^{179,196}

Hirsutism, dizziness, arthralgia, fatigue, hypokalaemia, and nausea are the most commonly reported adverse events with metyrapone; adrenal insufficiency, abdominal pain, and atopic dermatitis are less frequently reported.¹⁷⁹ Adverse events secondary to hyperandrogenism can limit prolonged treatment, especially in female patients.

Osilodrostat

Proof-of-concept and phase 2 prospective studies showed that osilodrostat, an 11 β -hydroxylase and aldosterone synthase inhibitor, was effective in reducing cortisol and was well-tolerated.^{188–190} This drug was further evaluated

in 137 patients with Cushing's disease enrolled in a phase 3, prospective, multicentre, double-blind, randomised withdrawal study.¹⁹¹ After 12 weeks of open-label dose-titrated treatment and 12 additional weeks of open-label dose-optimised treatment, 72 (53%) patients had maintained normal UFC and were eligible for randomisation. By week 34, at the end of the randomised treatment period, 31 (86%) of 36 randomly assigned to osilodrostat maintained normal UFC versus 10 (29%) of 35 randomly assigned to placebo (OR 13.7, 95% CI 3.7–53.4; $p < 0.0001$).

Treatment with osilodrostat also yielded clinical improvements. By week 48, patients showed decreases in bodyweight, blood pressure, total cholesterol, and LDL cholesterol compared with baseline, and decreased fasting serum glucose and HbA_{1c} concentrations. Quality of life and depression scores also improved.¹⁹¹

Nausea, anaemia, and headache were reported in 8–11% of patients, and adverse events related to hypocortisolism were reported in about half of patients, mostly during the open-label dose-titration period. These adverse events were generally manageable with dose reductions or interruptions, although glucocorticoid replacement was required in 25 (36%) of 70 patients with one or more hypocortisolism-related adverse events. Additionally, 58 (42%) of 137 treated patients in the phase 3 study showed effects from increased levels of adrenal steroid precursors, including hypokalaemia and hypertension; 12 (11%) of 106 women reported hirsutism.¹⁹¹ In another prospective phase 3 study of 44 patients, a significantly greater proportion of patients receiving osilodrostat (77%) achieved mean UFC below or equal to the ULN after 12 weeks of treatment versus placebo (8%), with improvements seen in clinical features, cardiovascular disease markers, and quality of life. Hypocortisolism-related adverse events occurred in 27% of patients.¹⁹²

Mitotane

Mitotane inhibits several steroidogenic enzymes and has a long-lasting adrenolytic action in steroid-secreting adrenocortical cells. It suppresses hypercortisolism in 80% of cases, but with a slow onset of action and highly variable bioavailability.^{180,198} Induction of CYP3A4-mediated rapid inactivation of cortisol leads to a requirement for a 2–3-times increased glucocorticoid replacement dose when treatment of adrenal insufficiency is needed, or with a block-and-replace strategy.¹⁸⁷ It is rarely used for Cushing's disease. Most workshop participants considered that use of mitotane should be limited to patients with adrenal carcinoma.

Etomidate

Originally developed as an anaesthetic, etomidate was shown to rapidly normalise cortisol concentrations, leading to use for acute control of severe hypercortisolism in patients treated in an intensive care setting.¹⁹⁹ Low-dose

etomidate (0.04–0.05 mg/kg/h) produces partial blockade; a high dose (0.5–1 mg/kg/h) provides for complete blockade, with intravenous hydrocortisone used to avoid etomidate-induced adrenal insufficiency.²⁰⁰ Very low doses (0.025 mg/kg/h) can be used in patients treated in hospital outside of intensive care,²⁰¹ although this might depend on local practice.

Compared with the lipid formulation, the propylene glycol preparation of etomidate is more frequently associated with thrombophlebitis and pain on injection, and also with additional adverse events, such as haemolysis and renal tubular injury, as well as lactic acidosis at high doses.²⁰⁰

Targeting pituitary somatostatin and dopamine receptors

Both the dopamine agonist cabergoline and the somatostatin receptor ligand pasireotide are used in patients with Cushing's disease who have persistent or recurrent hypercortisolism,^{7,139,179} although only pasireotide is approved by regulatory agencies for use in this population.^{7,204,205} Tumour control (shrinkage and growth prevention), which may be seen, is clinically important for patients with a large residual tumour and for patients with corticotroph tumour progression, or Nelson's syndrome.

Pasireotide

In a phase 3 study of 162 patients with Cushing's disease treated with subcutaneous pasireotide, UFC normalised at month 6 in 15–26% of those without dose increases. Higher rates of UFC normalisation were seen in patients with baseline UFC less than five times ULN²⁰⁴ and significant clinical improvement was noted in most patients.²⁰⁵

Another phase 3 study treated 150 patients with Cushing's disease with 10 mg or 30 mg monthly intramuscular pasireotide long-acting release (LAR). At month 7, 62 (40%) patients in both groups showed normalised UFC, regardless of dose titration, with highest response in those with baseline UFC less than two times ULN.²⁰⁷ At month 12, improvements in blood pressure were greater in those with normalised UFC than in those without normalised UFC; BMI, weight, waist circumference, and quality of life were all improved regardless of UFC control.²⁰⁸ Long-term extension studies showed that biochemical and clinical improvements could be maintained for up to 5 years in select patients who continued the study.^{209,210} Of note, in real-life settings, few data are available about long-term treatment compliance, and several studies show a high rate of treatment discontinuation. Treatment with pasireotide LAR also decreased median tumour volume by 17.8% with the 10 mg dose and 16.3% with the 30 mg dose. 15 (43%) patients who received the 10 mg dose and 18 (47%) who received the 30 mg dose had at least a 20% reduction in median tumour volume.²⁰⁷

A longitudinal study in five patients with Cushing's disease with Nelson's syndrome after bilateral adrenalectomy showed that pasireotide LAR rapidly suppressed ACTH concentrations and yielded sustained reductions over 24 weeks.²¹⁹

Between a third and two-thirds of Cushing's disease tumours harbour a mutation in *USP8*,^{220,221} and these mutated tumours can show higher *SST5* expression compared with wild-type tumours.^{222,223} Because pasireotide has a high affinity for this receptor, *USP8* mutational status might prove to be a useful marker for predicting treatment response.

The risk for hyperglycaemia is high with pasireotide.^{204,205,224–226} In the two phase 3 studies,^{204,207} approximately 70% of patients reported hyperglycaemia-related adverse events, with new antidiabetic medication initiation or dose adjustments required in approximately half of patients. The high rates of hyperglycaemia are thought to result from inhibition of insulin and incretin secretion combined with a lesser degree of glucagon inhibition.²¹⁵ Management with GLP-1 receptor agonists or DDP-4 inhibitors is therefore thought to be useful.^{226,227}

Cabergoline

Available data on cabergoline use in Cushing's disease are derived mostly from small retrospective studies demonstrating biochemical normalisation in 25–40% of patients, with loss of control in 20–40% of patients who are initially normalised.^{210,211}

A retrospective, multicentre cohort study of 53 patients treated with a median cabergoline dose of 2.3 mg per week (range 0.5–6.0) yielded normal UFC in 40% of patients during the first year, but only 23% of those showed sustained UFC normalisation after a median 32.5 months follow-up.²¹² The low control rate could be due to under-titration, as a smaller study of 20 patients on cabergoline titrated to maximum of 7 mg per week (median 3.5 mg per week) showed normalised UFC in eight (40%) of patients at 24 months.²¹³ Weight, glycaemic control, and hypertension improved in 25–40% of complete responders,²¹² and tumour shrinkage was reported in 50%.²¹³ Patients with Nelson's syndrome can also respond to cabergoline, and both ACTH normalisation and tumour shrinkage have been reported.²²⁸ Although not approved in this setting, cabergoline has been used in pregnant patients with prolactinomas and other pituitary adenomas, including Cushing's disease.¹⁷⁹

Cabergoline-induced impulse-control disorder is probably under-reported, and can manifest as hypersexuality, pathological gambling, excessive alcohol consumption, overeating, and uncontrolled shopping.²¹⁴ This behaviour can occur within months of initiating cabergoline therapy, or might manifest later, and improves or resolves after treatment discontinuation.^{229,230}

High cumulative doses of ergotamine-derived dopamine agonists used in patients with Parkinson's disease were associated with risk of cardiac valve

regurgitation.²³¹ Although one study in prolactinomas found that moderate tricuspid regurgitation was more frequent with higher doses,²³² a large multicentre study

found no association between the cumulative cabergoline dose and age-corrected prevalence of any valvular abnormality.²³³ Furthermore, a meta-analysis showed that

Panel 3: Medical therapy for Cushing's disease

Which factors are helpful in selection of a medical therapy?

- If there is a need for rapid normalisation of cortisol, we recommend an adrenal steroidogenesis inhibitor; osilodrostat and metyrapone have the fastest action and are orally available, while etomidate can be used intravenously in very severe cases (high quality, strong recommendation)
- In mild disease, if residual tumour is present and there is a potential for tumour shrinkage, consider pasireotide or cabergoline (moderate quality, strong recommendation)
- If there is a history of bipolar or impulse control disorder, consider avoiding cabergoline (moderate quality, strong recommendation)
- If an expert pituitary endocrinologist is not available to monitor treatment response, use mifepristone cautiously (low quality, discretionary recommendation); we recommend counselling patients that cortisol cannot be used to monitor treatment response or adrenal insufficiency (high quality, strong recommendation). Drug–drug interactions must be considered when this medication is used
- In pregnant women or those desiring pregnancy, consider cabergoline or metyrapone (low quality, discretionary recommendation), although no Cushing's disease medications are approved for use in pregnancy
- Drug intolerance or side-effects, as well as concomitant comorbidities such as type 2 diabetes and hypertension, should further guide type of medication used (moderate quality, strong recommendation)
- Consider cost and estimated therapy duration, especially if definitive treatment (ie, pituitary or adrenal surgery) is planned or while awaiting effects of radiotherapy (low quality, discretionary recommendation)

Which factors are used in selecting an adrenal steroidogenesis inhibitor?

- Rapidity of action, tolerability, ease-of-use, degree of probable biochemical normalisation, and specific clinical improvement, as well as local availability and cost of each drug, should be considered at therapy start (moderate quality, strong recommendation)
- Ketoconazole might be favoured for ease of dose titration; concern about inducing hepatotoxicity and the need to monitor liver enzymes can lead to under-dosing (moderate quality, strong recommendation). Drug–drug interactions must be considered and hypogonadism may occur in men
- Osilodrostat achieves high rates of cortisol normalisation. Dosing schedule might be more convenient for patients than with metyrapone, but neither metyrapone nor osilodrostat is limited by hypogonadism in men (high quality, strong recommendation)
- Mitotane is rarely used as monotherapy in Cushing's disease in most centres (low quality, discretionary recommendation)

How is tumour growth monitored when using an adrenal steroidogenesis inhibitor or glucocorticoid receptor blocker?

- MRI is typically obtained 6–12 months after initiating treatment and repeated every few years depending on the clinical scenario (moderate quality, strong recommendation)
- It can be difficult to determine whether tumour progression is due to loss of cortisol feedback or reflects the underlying behaviour of aggressive, recurrent disease (low quality, discretionary recommendation)
- We suggest monitoring ACTH concentrations, because progressive elevations in ACTH could be a sign of tumour growth and a need for MRI; although the half-life of ACTH is short, concentrations fluctuate, and they do not necessarily reflect tumour growth (low quality, discretionary recommendation)
- If progressive tumour growth is seen, medical treatment should be suspended and the management plan reassessed (moderate quality, strong recommendation)

When is preoperative medical therapy used?

- There are no rigorous data supporting use of preoperative medical therapy (moderate quality, strong recommendation)
- Most experts would consider use of adrenal steroidogenesis inhibitors if surgery is delayed, either because of scheduling or because of external factors (low quality, discretionary recommendation)
- Patients with severe Cushing's disease who have potentially life-threatening metabolic, psychiatric, infectious, or cardiovascular or thromboembolic complications might benefit from preoperative medical therapy in select cases (low quality, discretionary recommendation)

How is treatment response monitored? Which factors are considered in deciding whether to use combination therapy or to switch to another therapy?

- Response should be defined on the basis of a combination of clinical endpoints (eg, improved phenotype, weight, hypertension, glucose metabolism, quality of life) and biochemical endpoints, or only clinical endpoints when glucocorticoid receptor blockers are used (moderate quality, strong recommendation)
- Cortisol concentrations are often measured by urinary free cortisol (except when using mifepristone); urinary free cortisol is not useful if adrenal insufficiency is a concern and morning serum cortisol is preferred (high quality, strong recommendation)
- Because of the loss of biological circadian rhythm, it is unclear whether targeting diurnal secretion alone with morning cortisol or with late-night salivary cortisol is meaningful (low quality, discretionary recommendation)

(Panel 3 continues on next page)

(Continued from previous page)

- Change in treatment should be considered if cortisol levels are persistently elevated after 2–3 months on maximum tolerated doses (moderate quality, strong recommendation)
 - If cortisol does not normalise but is reduced or there is some clinical improvement, combination therapy can be considered (low quality, discretionary recommendation)
 - If there is clear resistance to treatment despite dose escalation, we suggest switching to a different therapy (low quality, discretionary recommendation)
- Which drugs are used for optimal combination therapy?**
- There are few rigorous data supporting specific regimens for combination therapy (high quality, strong recommendation)
 - Many experts consider combining ketoconazole with metyrapone or potentially ketoconazole with osilodrostat to maximise adrenal blockade when monotherapy is not effective, or to allow lower doses of both drugs (low quality, discretionary recommendation)
 - Ketoconazole plus cabergoline or pasireotide, and pasireotide plus cabergoline could be rational combinations if there is visible tumour present (low quality, discretionary recommendation)
 - Other combinations that can be used include triplets of cabergoline, pasireotide, plus ketoconazole, and ketoconazole, metyrapone, plus mitotane (low quality, discretionary recommendation)

it remains an open question whether such echocardiographic findings are clinically significant.²³⁴

Targeting the peripheral tissue glucocorticoid receptor *Mifepristone*

The glucocorticoid receptor blocker mifepristone is effective in controlling some effects of hypercortisolism, regardless of the cause.

An open-label study of 50 patients with endogenous Cushing's syndrome, including 43 with Cushing's disease, showed that after 24 weeks of treatment, 15 (60%) of 25 patients with a concurrent diagnosis of type 2 diabetes or impaired glucose tolerance had a significant reduction of at least 25% from baseline in area under the curve for glucose during an oral glucose tolerance test, and eight (38%) of 21 patients with hypertension showed a significant reduction of at least 5 mm Hg in diastolic blood pressure. Insulin resistance, weight, waist circumference, and quality of life also improved.²¹⁵

Twelve patients had increased blood pressure, including nine with hypokalaemia who required spironolactone, consistent with mineralocorticoid receptor activation. Endometrial hypertrophy and irregular menstrual bleeding were also reported, consistent with the anti-progesterone activity of mifepristone. Dexamethasone was administered in seven patients with signs and symptoms of adrenal insufficiency, underscoring the need for careful monitoring.²¹⁵ Cortisol concentrations remain high despite treatment with mifepristone, and measures of low cortisol typically used to confirm adrenal insufficiency due to overtreatment with other medical therapies cannot be used with mifepristone. Rather, only clinical features can be used.²¹⁶

Continued mifepristone treatment of 27 patients with Cushing's disease included in a long-term extension study showed sustained increases in ACTH concentrations of at least two times, but tumour volume progression, seen in three patients with macroadenomas up to 25 months from baseline, did not correlate with ACTH increases.²¹⁷

Thyroid function should be closely monitored and thyroid hormone replacement adjusted as needed.²¹⁸ All concomitant medications should be carefully reviewed given the potential for drug–drug interactions with mifepristone.

Clinical considerations and recommendations for medical therapy

We recommend individualising medical therapy for all patients with Cushing's disease based on the clinical scenario, including severity of hypercortisolism. Regulatory approvals, treatment availability, and drug costs vary between countries and often influence treatment selection. However, where possible, it is important to consider balancing cost of treatment with the cost and the adverse consequences of ineffective or insufficient treatment. In patients with severe disease, the primary goal is to treat aggressively to normalise cortisol concentrations (or cortisol action if using mifepristone). Multiple serial tests of both UFC and LNSC are used to monitor treatment outcomes.^{158,235,236}

A brief summary of workshop discussions about how to best incorporate each of the different treatment options is presented in panel 3 and in figure 2.

Initial treatment selection for medical therapy

Adrenal steroidogenesis inhibitors are usually used first given their reliable effectiveness. For patients with mild disease and no visible tumour on MRI, ketoconazole, osilodrostat, or metyrapone are typically preferred. Cabergoline can also be used for mild Cushing's disease; it is less effective and has a slower onset of action, but requires less frequent dosing than the drugs previously described. For patients with mild-to-moderate disease and some residual tumour, there might be a preference for cabergoline or pasireotide because of the potential for tumour shrinkage. However, the high rate of hyperglycaemia with pasireotide would make patient selection crucial.

For patients with severe disease, rapid normalisation of cortisol is the most important goal. With osilodrostat and metyrapone, response will typically be seen within hours, and with ketoconazole within a few days. Intravenous etomidate also works rapidly and could be used if the patient cannot take oral medications. For patients with severe hypercortisolism, combinations of steroidogenesis inhibitors might be necessary. However, if hypercortisolism is severe and not responsive to optimised medical therapy, including combinations, bilateral adrenalectomy should be considered to avoid worsening outcomes.

Other patient factors can be important for initial treatment selection. For example, cabergoline should not be used in patients with a history of bipolar or impulse

control disorder, but might be preferred in a young woman desiring pregnancy. Although none of these drugs are specifically approved for use in pregnancy, metyrapone might be considered with precautions in selected women who are pregnant. In such cases, given the higher normal cortisol levels during pregnancy, a higher cut-off target for cortisol (eg, $1.5 \times \text{ULN}$) is used.

Mifepristone improves key clinical features associated with hypercortisolism, specifically hyperglycaemia and weight gain. However, it could be challenging to use in standard clinical practice, and often worsens hypokalaemia. There are no reliable biochemical markers for monitoring cortisol concentrations, increasing the risk of adrenal insufficiency due to overtreatment, and the long

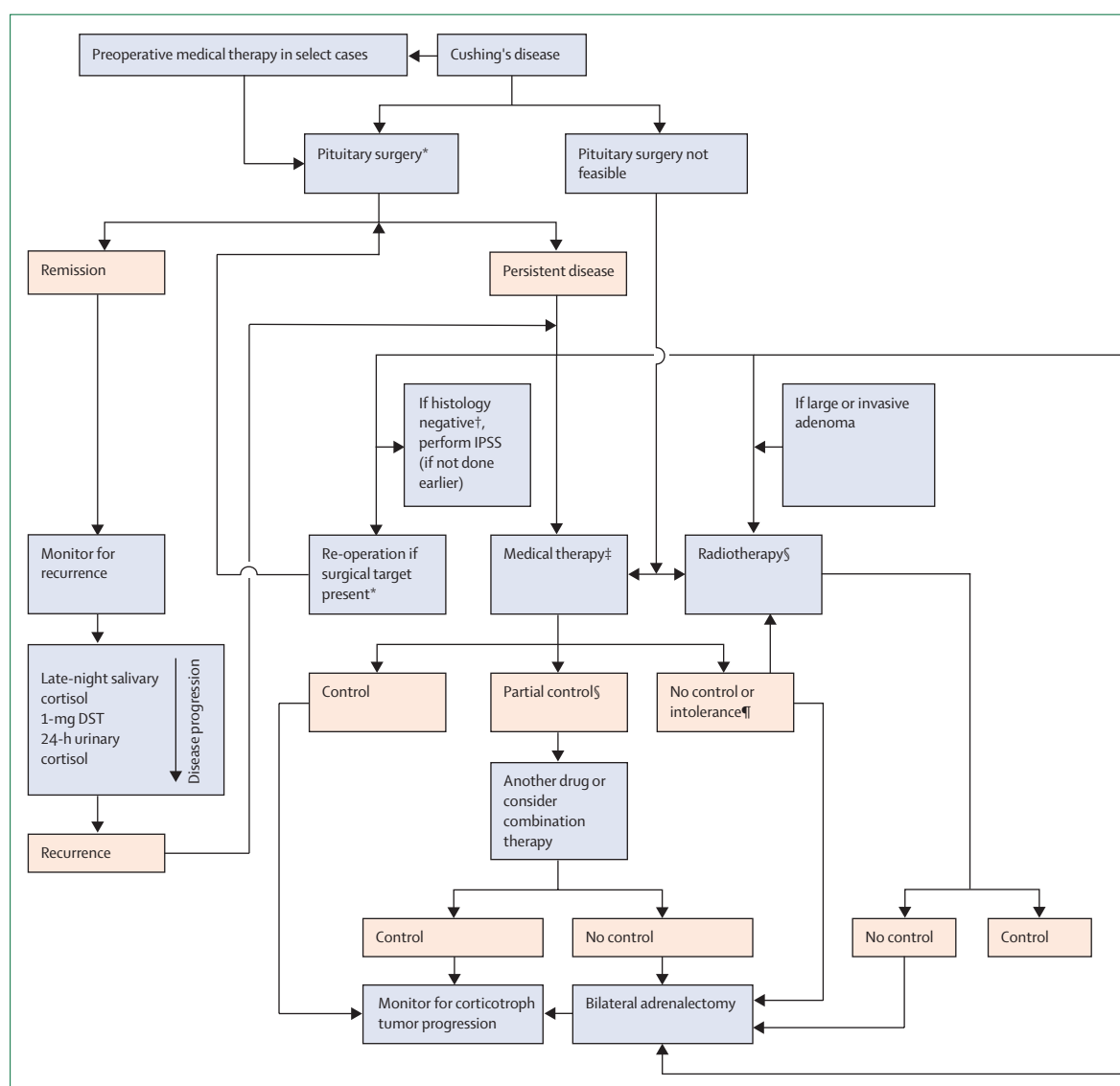


Figure 2: Algorithm for management of Cushing's disease

DST=dexamethasone suppression test. IPSS=inferior petrosal sinus sampling. ACTH=adrenocorticotropic hormone. *Pituitary surgery should be performed by an experienced surgeon. †Absence of ACTH-staining adenoma. ‡See table 2 and panel 3 for considerations regarding selection of medical therapy. §Lifelong monitoring for hypopituitarism and secondary neoplasia in the radiation field required. ¶On maximum tolerated dose of the drug.

half-life of mifepristone and its metabolite requires several days of stress-dose glucocorticoid replacement, preferably dexamethasone, if adrenal insufficiency ensues. Because cortisol measurements are not helpful for dosing or safety monitoring, mifepristone should be used only by clinicians with extensive experience in Cushing's disease; it is also important to counsel patients that monitoring cortisol concentrations is not reliable, especially for adrenal insufficiency.

There are few rigorous data supporting specific regimens for combination therapy, but several have been described.^{197,237,238} Many experts consider combining ketoconazole with metyrapone to maximise adrenal blockade when monotherapy is not effective or to allow lower doses of both drugs, although a steroidogenesis inhibitor plus a tumour-targeting agent, such as ketoconazole plus cabergoline, is also a rational combination, especially if visible tumour is present. Other combinations that could be used include triplets of cabergoline, pasireotide, plus ketoconazole; and metyrapone, ketoconazole, plus mitotane. Risk of potentiating adverse effects with combination therapy, such as QTc prolongation, should also be considered.

Selecting an adrenal steroidogenesis inhibitor

The longest clinical experience for adrenal steroidogenesis inhibitors is with ketoconazole and metyrapone. These agents are approved for use in Cushing's disease in Europe by the EMA, but not in the USA (where only osilodrostat is approved in this category by the FDA), and they might not be available in some countries. Ketoconazole might be favoured for ease of dose titration, but it is often under-dosed for fear of inducing hepatotoxicity. Liver function tests should be regularly monitored, but treatment does not necessarily have to be discontinued if liver function tests are mildly elevated, yet stable.²³⁹ Osilodrostat and metyrapone can induce rapid control in the majority of patients. They are not limited by monitoring of liver function tests and hypogonadism does not occur in men. It is expected that osilodrostat will be increasingly used as it becomes widely available given its high efficacy and twice-daily dosing. It is necessary to monitor for adrenal insufficiency and osilodrostat effects on androgens, but whether treatment selection should be based on patient sex in long-term treatment is not yet known. Mitotane, rarely used for patients with Cushing's disease in most centres, has a slower onset of action.

A block-and-replace regimen could be considered for patients with severe disease or cyclical Cushing's syndrome, and in patients ineligible for surgery. This might be a particularly useful approach if monitoring visits are infrequent because of external factors such as the COVID-19 pandemic, lack of transportation, or other issues. Caution is needed to avoid glucocorticoid over-replacement and inducing iatrogenic Cushing's syndrome.

Monitoring response to medical therapy

For all patients, regular monitoring for treatment efficacy is required, including measures of cortisol (except with mifepristone) and patient symptoms and comorbidities, especially weight, glycaemia, and blood pressure. In addition, quality of life is important to take into account, preferably through patient-reported outcomes. Cortisol concentrations are often measured by UFC; notably, this test is not useful for diagnosis of adrenal insufficiency. Morning cortisol, LNSC, or both could be used as an alternative, but because of the loss of circadian rhythm, it is unclear whether targeting diurnal secretion alone is meaningful. Nevertheless, morning cortisol values might be especially pertinent in patients taking higher medication doses in the evening than in the morning.¹⁸² Patients who normalised both UFC and LNSC with pasireotide LAR had better clinical outcomes than those who normalised UFC alone,²³⁵ and a higher treatment dose at bedtime for twice daily medications might help restore circadian rhythm patterns, but there is no rigorous evidence to support the latter approach.

As designs, medication up-titration schemes, comparator arms, inclusion and exclusion criteria, and primary endpoints differ even among prospective studies, it is difficult to directly compare treatment outcomes, either for efficacy or for adverse effects. Furthermore, some drugs have not been prospectively studied for Cushing's syndrome. When using UFC normalisation as a target, osilodrostat has the highest efficacy on the basis of data from several prospective clinical trials, followed by metyrapone (retrospective and prospective data), ketoconazole (retrospective data), pasireotide (prospective data), and cabergoline (retrospective and prospective data). Because improvement in clinical features of Cushing's syndrome and diabetes are used as markers of mifepristone efficacy, this drug cannot be directly compared for biochemical efficacy with other available treatments.

Change in treatment should be considered if cortisol concentrations are persistently elevated after 2–3 months on maximum tolerated doses. If cortisol does not normalise but is reduced or there is some clinical improvement, combination therapy can be considered. If there is clear resistance to treatment, we suggest switching to a different therapy. However, it is important to ensure that insufficient disease control due to under-dosing is not misinterpreted as treatment resistance.

With adrenal-targeting agents, there can be concern for tumour growth due to ACTH-cortisol feedback interruption. However, it can be difficult to determine whether such tumour progression is due to this loss of feedback or reflects the underlying behaviour of aggressive, recurrent disease. We suggest monitoring ACTH concentrations, as substantial increases could portend new tumour growth and a need for MRI, with the caveats that ACTH has a short half-life and concentrations fluctuate, and so they might not necessarily reflect tumour growth. If progressive increase in tumour size is noted,²⁴⁰ treatment should be

suspended and management reassessed. MRI is typically done 6–12 months after initiating treatment and repeated every few years, depending on the clinical scenario.

With combination therapies, it is also important to monitor for potential overlapping toxicities, particularly QTc prolongation, as well as drug–drug interactions.

Primary and preoperative medical therapy for de novo Cushing's disease

Primary medical therapy is used when successful adenoma resection is unlikely because of unfavourable localisation, clinically significant invasiveness, or lack of visualisation on MRI. Double-blind, randomised phase 3 studies evaluating the efficacy of several novel drugs included a small proportion of patients with de novo Cushing's disease, ranging from 0% to 28%.¹⁸⁷ Further studies are needed to demonstrate utility of the different medical therapies in this setting, either as monotherapy or in combination, while also taking into account the potential effects of such treatment on adenoma size.

Published evidence regarding preoperative medical therapy in patients with Cushing's disease is sparse, and it is not used in most patients, although there are regional variations. A meta-analysis showed no differences in cortisol normalisation rate between participants who received cortisol-lowering medications in the preoperative setting versus later use as adjuvant treatment.²⁴¹ Preoperative medical therapy could be an option in severely ill patients for whom surgery is contraindicated or if waiting time for surgery is long,¹³⁹ or in patients with life-threatening complications of hypercortisolism requiring rapid cortisol control.²⁴² Physician surveys show that preoperative therapy, mostly with ketoconazole or metyrapone, is used in up to 20% of patients with Cushing's disease, especially those with more severe clinical features or nonvisible adenoma.²⁴³

Retrospective studies show that therapy with preoperative steroidogenesis inhibitors for a mean of 4 months yields cortisol normalisation rates of 50–72%, although subjective symptom improvement was observed in only a third of cases.^{185,193} Lower rates of postoperative hypoadrenalism from preoperative medical therapy could, in theory, protect against the occurrence of a proinflammatory and pro-coagulant state,^{94,243} but postsurgical complications, including VTE, are similar regardless of its use.²⁴³ If the HPA axis recovers during preoperative treatment, adrenal insufficiency might not occur postoperatively, so it can be more difficult to determine whether remission is present.

Preoperative cabergoline probably has limited value, because a substantial decrease in cortisol was seen in only a quarter of patients in a cohort treated prospectively for 6 weeks.²⁴⁴

Clinical considerations and recommendations for primary and preoperative medical therapy for de novo Cushing's disease

There are no rigorous data supporting use of primary or preoperative medical therapy. Most experts would consider

such an approach with adrenal steroidogenesis inhibitors if surgery is delayed, either because of scheduling or due to external factors such as a pandemic (very low quality, discretionary recommendation).

Patients with severe Cushing's disease who have potentially life-threatening metabolic, psychiatric, infectious, or cardiovascular or thromboembolic complications might also benefit from preoperative medical therapy in select cases (low quality, discretionary recommendation). Although this benefit has not been clearly confirmed, some experts consider it might have a potentially favourable effect on glucose, cardiovascular, and coagulation parameters (very low quality, discretionary recommendation). Few experts use it to decrease the extent of postoperative cortisol withdrawal manifestations.

Monitoring and follow-up of patients treated with preoperative therapy can be challenging because postoperative cortisol assessments for surgical cure are not reliable. The patient's perspective regarding this approach would be valuable to incorporate into future research studies (very low quality, discretionary recommendation).

Radiotherapy

Radiotherapy is primarily used as adjuvant therapy for patients with persistent or recurrent disease after transphenoidal surgery^{7,245} or for aggressive tumour growth. Approximately two-thirds of patients achieve biochemical remission during the years after treatment with conventional external-beam radiotherapy, typically 45–50 Gy administered in less than 2 Gy fractions, or stereotactic radiosurgery, which is administered as single dose or a few fractions of approximately 20 Gy.²⁴⁶ However, more recent series with stereotactic radiosurgery, including whole sellar radiotherapy,²⁴⁷ show higher biochemical remission rates. In a multicentre study of GammaKnife stereotactic radiosurgery in 278 participants followed for a mean of 5.6 years, biochemical control was attained in 193 (80%) and durable hypercortisolism control was maintained in 158 (57%).²⁴⁸ Tumour control rates are typically higher, with approximately 95% of patients treated with stereotactic radiosurgery showing decreased or stable tumour volume as observed on MRI.²⁴⁶ A small single-centre study of proton-beam radiotherapy showed complete response (either cortisol or ACTH normalisation) in patients with persistent corticotroph adenomas due to Cushing's disease or Nelson's syndrome, with low morbidity after a median follow-up of 62 months.²⁴⁹

Stereotactic radiosurgery can also be used as primary therapy in patients with high surgical risk or who refuse surgery. In this setting, endocrine remission was attained in 17 (81%) of 21 patients with Cushing's disease at 5 years of follow-up.²⁵⁰ Long-term follow-up is needed as recurrence and tumour growth have been described post-radiotherapy.

Given the latency until post-radiotherapy remission, adjuvant medical therapy is needed to control hypercortisolism; periodic withdrawal allows evaluation of

cortisol secretion to assess treatment effect.⁷ Although data are mixed on whether ketoconazole^{248,251} or cabergoline²⁵² treatment at the time of stereotactic radiosurgery limits efficacy, they are often withheld temporarily at the time of radiotherapy.

Hypopituitarism is the most common side-effect of both conventional radiotherapy and stereotactic radiosurgery, seen in 25–50% of patients, and generally increases over time. Risk of secondary malignancy, cranial nerve damage, and stroke are low with stereotactic radiosurgery.²⁵³ In patients treated with stereotactic radiosurgery, a distance of at least 3–5 mm between the tumour and the optic chiasm and a chiasm dose less than 8 Gy is recommended to limit treatment damage.²⁵³ Long-term data will help address whether use of different stereotactic radiosurgery modalities (eg, GammaKnife, linear accelerator, proton beam) confers lower rates of stroke and hypopituitarism compared with conventional radiotherapy.²⁵⁴

Clinical considerations and recommendations for radiotherapy

Radiotherapy is most commonly used in cases of persistent hypercortisolism after incomplete corticotroph tumour resection, particularly if the tumour is aggressive or invasive or is considered unresectable (high quality, strong recommendation). Stereotactic radiosurgery is probably more convenient as few treatment sessions are required, but avoiding optic chiasm exposure is crucial (high quality, strong recommendation). Lifelong monitoring for pituitary hormone deficiencies and recurrence is required in all patients undergoing radiotherapy (high quality, strong recommendation). Imaging for secondary neoplasia in the radiation field should also be considered (high quality, strong recommendation).

Adrenalectomy

Bilateral adrenalectomy offers immediate control of cortisol excess in patients with persistent or recurrent Cushing's disease that is not responsive to medical therapy,^{7,139,255} but it is only considered for selected patients because of the resultant adrenal insufficiency and need for life-long glucocorticoid and mineralocorticoid replacement therapy.²⁵⁶ Laparoscopic bilateral adrenalectomy using either a transperitoneal or posterior retroperitoneal approach was associated with a 10–18% complication rate and a mortality rate of less than 1% in the largest series.^{257,258} Long-term clinical relapse of hypercortisolism due to adrenal rest stimulation by high ACTH is uncommon (<10%), whereas clinical improvement in BMI, type 2 diabetes, hypertension, and muscle weakness has been reported in more than 80% of patients.²⁵⁹

Corticotroph tumour progression after bilateral adrenalectomy is a long-term concern in 25–40% of patients after 5–10 years.^{259–261} Most cases can be managed with surgery, radiotherapy, or medical therapy. However, a subset of aggressive tumours will continue to grow and

long-term monitoring is required. A European consensus focused on management of these patients was published in 2021.²⁶²

Corticotroph tumour progression after bilateral adrenalectomy does not seem to be influenced by pregnancy.²⁶³ This might make bilateral adrenalectomy a preferred option in female patients with an immediate pregnancy plan. In most cases, however, bilateral adrenalectomy is rarely performed as the first-line treatment after failure of initial pituitary surgery, and duration of disease before adrenal surgery is typically 3–4 years or longer.²⁵⁸ Whether and how this might affect long-term treatment outcomes remains unknown.

Clinical considerations and recommendations for adrenalectomy

In patients with Cushing's disease, bilateral adrenalectomy is often considered to be a treatment of last resort in most centres after all other options have failed (moderate quality, strong recommendation). However, bilateral adrenalectomy can be warranted earlier in patients with severe hypercortisolism in whom a rapid, definitive effect on cortisol is needed to avoid prolonged systemic effects of uncontrolled disease (moderate quality, strong recommendation). Many expert centres recommend bilateral adrenalectomy earlier in the course of the disease for female patients with Cushing's disease desiring pregnancy (moderate quality, strong recommendation).

After bilateral adrenalectomy, plasma ACTH and serial pituitary imaging are used for monitoring at intervals dictated by the clinical scenario, usually starting 6 months after surgery (high quality, strong recommendation). More frequent evaluation might be necessary if there is a clinical suspicion of corticotroph tumour progression (high quality, strong recommendation).

Additional considerations

Genetics of Cushing's disease

Corticotroph adenomas are predominantly of sporadic origin, based on a monoclonal expansion of a singular mutated cell.²⁶⁴ These adenomas abundantly express EGFR, which signals to induce ACTH production.²⁶⁵ Somatic activating driver mutations in *USP8* are present in 36–60% of corticotroph adenomas.²¹¹ These mutations lead to persistent overexpression of EGFR, thereby perpetuating the hyper-synthesis of ACTH. Rarely, mutations in the glucocorticoid receptor *NR3C1*, the *BRAF* oncogene, the deubiquitinase *USP48*, and *TP53* are encountered.²⁶⁴ Patients with familial tumour syndromes, such as *MEN1*, *FIPA*, and *DICER1*, rarely develop corticotroph adenomas. It has been proposed that corticotroph tumours could be sub-classified on the basis of *USP8* driver mutations and clinical behaviour.²⁶⁶ As *USP8* mutational status might predict recurrence after transsphenoidal surgery,²⁶⁷ such genomic classifications could open new avenues for more targeted, personalised treatment modalities in the future.

Diagnosis and management of Cushing's syndrome in children

Endogenous Cushing's syndrome is very rare before age 18 years. Germline mutations in *MEN1*, *RET*, *AIP*, *PRKARIA*, *CDKN1B*, *DICER1*, *CABLES1*, and *SDH*-related genes can all predispose children to Cushing's disease, although screening is usually reserved for cases in which there is either family history or other signs suggestive of a genetic syndrome.²⁶⁸

Lack of height increase concomitant with weight gain is the most common Cushing's syndrome presentation in children, making the disorder somewhat easier to detect than in post-pubertal adolescents or adults. Using the insulin tolerance or glucagon stimulation test, prevalence of severe growth hormone deficiency (<9 mU/L) is estimated at 31% and partial growth hormone deficiency (<30 mU/L) is estimated at 54%.²⁶⁹

Documentation of hypercortisolism with 24-h UFC, LNSC, or overnight 1 mg DST are all used to confirm diagnosis. The diagnostic approach and test performances are slightly different from adults, as recently extensively reviewed.²⁷⁰ The Dex-CRH test is not useful in children. In children older than 6 years, Cushing's disease is the most common cause of Cushing's syndrome, whereas adrenal causes are more common in younger children. There are algorithms for testing to distinguish ACTH-dependent from ACTH-independent Cushing's syndrome. Notably, the role of IPSS in children is more limited than in adults.²⁷¹

As in adults, surgical resection of the ACTH-secreting tumour is the first-line treatment in children. However, unlike in adults, thromboprophylaxis should not be routinely used because of bleeding risk, but is reserved for selected paediatric patients. With successful treatment, adrenal function typically recovers within approximately 12 months.²⁷² Evaluation for growth hormone deficiency should be done by 3–6 months postoperatively, and immediate growth hormone replacement given if needed to ensure proper growth; growth hormone replacement ensures adequate final height, but obesity is not fully reversible.²⁷³ For paediatric patients requiring medical therapy, ketoconazole or metyrapone is typically used with morning cortisol for monitoring response. Pasireotide is not recommended and clinical trials of osilodrostat in children are underway. Block-and-replace regimens with metyrapone can also be considered.

Early diagnosis and expert management are crucial given the potential for long-term adverse health outcomes from prolonged hypercortisolism and from morbidity associated with transsphenoidal surgery or radiotherapy. Children with Cushing's syndrome should be referred to multidisciplinary centres of excellence with paediatric endocrinologists expert in managing disorders of the pituitary, and with specialised neurosurgery units. If an underlying genetic syndrome is present, genetic counselling for the child and family members, as well as investigations into

Panel 4: Future research topics ranked of highest importance

Screening and diagnosis of Cushing's syndrome

- Optimise pituitary MRI and PET imaging using improved data acquisition and processing to improve microadenoma detection
- Compare diagnostic algorithms for the differential diagnosis using invasive versus non-invasive strategies
- Identify additional corticotroph adenoma mutations and develop a comprehensive panel of genomic and proteomic tests for corticotroph adenomas

Complications of Cushing's disease

- Define use of anticoagulant prophylaxis and therapy in different populations and settings
- Optimise the approach in managing long-term complications

Treatment of Cushing's disease

- Determine clinical benefit of restoring the circadian rhythm, potentially with a higher night-time medication dose
- Identify better markers of disease activity and control
- Develop new, better tolerated, more effective medical therapies
- Define populations that might benefit from preoperative medical treatment

Search strategy and selection criteria

References for this review were identified through searches of PubMed for articles published from Jan 1, 2015, to April 30, 2021, using the terms "diagnosis," "urinary free cortisol," "salivary cortisol," "screening tests," "confirmatory testing," "differential diagnosis," "localization testing," "genetics," "surgery," "radiation therapy," "medical therapy," "biochemical treatment goals," "tumor shrinkage," "clinical outcomes," "adrenal steroidogenesis inhibitors," "glucocorticoid receptor blockers," "somatostatin receptor ligands," "dopamine agonists," "mortality," "comorbidities," "quality of life," "preoperative treatment," "combination therapy," and "guidelines" in combination with the terms "Cushing's disease" and "ectopic Cushing's". English-language articles resulting from these searches and relevant references cited in those articles were reviewed.

other disorders associated with the syndrome, are necessary.^{270,274,275}

Conclusions

Academic investigators and clinical experts from 13 countries across five continents gathered virtually to discuss recent evidence regarding Cushing's disease. Consensus was reached on many recommendations for diagnosis and management; these have been presented, along with highlighted areas needing further research in this challenging condition (panel 4).

Contributors

MF, BMKB, AGi, and SM initiated and conceived the consensus meeting. MF and BMKB served as co-chairs and project administrators and supervisors. MF, BKMB, JN-P, NK, MGa, AT, SP, LN, PM, AGi, and SM served as steering committee members; developed the workshop topics; identified expert speakers, participants, and breakout group assignments and moderators; and developed the first draft of the manuscript on the

basis of speaker slide-lecture presentations and précis, and participant breakout discussion comments. MF, BMKB, EVV, GV, and SM contributed to development of the tables, figures, and panels. MF, BMKB, AGI, SM, JN-P, NK, MGa, AT, SP, LN, PM, EVV, GV, RA, IB, AB-S, JB, NRB, CLB, MDB, MB, JDC, FFC, FC, PC, JF, EBG, AGr, MGU, KH, AGI, UBK, LK, DFK, AL, AM, MM, AMP, RP, HR, MR, RS, CS, IS, CAS, BS, AT, YT, MT, ST, EV, JW, SMW, and MCZ reviewed the entire manuscript, approved the final version, and made the decision to submit.

Declaration of interests

MF has received grants to her institution from Novartis, Strongbridge, Novo Nordisk, Crinetics, Millendo, Ascendis, and Pfizer; personal honoraria for consulting and advisory boards from Crinetics, HRA Pharma, Novartis, Recordati, Strongbridge, Sparrow, Ascendis, Novo Nordisk, and Pfizer; and has served on the Board of the Pituitary Society. RA has received grants to his institution from Strongbridge Biopharma, Novartis Pharmaceuticals, and Corcept Therapeutics, and personal honoraria for consulting and advisory boards from Strongbridge Biopharma, Recordati Rare Diseases, Corcept Therapeutics, and Novartis Pharmaceuticals. IB has received grants and fees for consulting, advisory boards, and authorship to her institution from the National Institutes of Health (NIH), Strongbridge, Corcept, HRA Pharma, Sparrow Pharmaceuticals, Adrenas Pharmaceuticals, and Elsevier, and non-financial support to her institution from HRA Pharma. AB-S has received personal honoraria for advisory boards from Recordati. JB has received grants to his institution from Novartis, HRA Pharma, and Recordati, and personal honoraria for consulting, lectures, and meeting attendance from Novartis, HRA Pharma, Ipsen, and Recordati. NRB has served on the Board or as an advisor for European Neuroendocrine Association and the European Reference Network on Rare Endocrine Conditions. CLB has received grants and personal honoraria for lectures from Novartis and served on the Board or as an advisor for Sociedade Brasileira de Endocrinologia e Metabologia, Endocrine Society, and European Society of Endocrinology. MDB has received grants as principal investigator from Novartis. JDC has received grants to his institution from Novartis, Strongbridge, and Crinetics; personal honoraria for consulting and authorship from Recordati, Novo Nordisk, Corcept, and Merck Manual; and served on the Board or as an advisor for Pituitary Society, Endocrine Society, and American Association of Clinical Endocrinologists. FFC has served on the Board of the Pituitary Society. FC has received personal honoraria for consulting, lectures, and support for meeting attendance from Recordati Rare Diseases, Ipsen, and HRA Pharma. PC has received grants and honoraria to his institution for consulting and lectures from Novartis and Recordati. JF has received grants to his institution from Novartis and personal honoraria for consulting and advisory boards from Corcept, Recordati, and Novartis. MGa has received non-financial support from Novartis and Recordati and served on the Board or as an advisor for Pituitary Society and Brazilian Society of Endocrinology and Metabolism. EBG has received grants and personal honoraria for consulting, lectures, and advisory boards from Novartis, Corcept, Strongbridge, Bristol-Myers Squibb, Recordati, and HRA Pharma; and has served as an advisor for Cushing's Support & Research Foundation. AGI has received grants to his institution from Pfizer and personal honoraria for consulting and advisory boards from Abiogen, Novo Nordisk, and Recordati; and has served on the Board or as an advisor to European Society of Endocrinology and Glucocorticoid Induced Osteoporosis Skeletal Endocrinology Group. AGr has served as an advisor to Novartis and as an editor for *Neuroendocrinology* and *Journal of Neuroendocrinology*. MGU has received personal honoraria for consulting and lectures from Recordati Rare Diseases UK, HRA Pharma, and Ipsen; and is a Board member or advisor for UK Society for Endocrinology and European Society of Endocrinology. AGI has received grants to her institution from Recordati, Novartis, and Strongbridge; and personal honoraria for consulting from Recordati, HRA Pharma, and Strongbridge. UBK has received grants as co-investigator from Corcept; personal honoraria for consulting, advisory board, and lectures from Acerus Pharmaceuticals and Novo Nordisk; and serves as editor for *Journal of Clinical Endocrinology and Metabolism* and as Board member for Endocrine Society. NK has received personal honoraria for consulting from Recordati Rare Diseases and HRA Pharma, and has served as Board member or advisor for Pituitary Society, European Neuroendocrine Association, Endocrine Society, and European Society of Endocrinology.

LK has received personal honoraria for consulting from Strongbridge and Recordati. DFK has received royalties from Mizuho. AL has received grants from Recordati and Corcept; personal honoraria for lectures, support for meeting attendance, and advisory boards from Pfizer, Ipsen, Corcept, and the European Journal of Endocrinology; royalties from UpToDate Endocrinology; and served as a Board member for International Society of Endocrinology. AM has received grants and personal honoraria for lectures or presentations and support for meeting attendance from Pfizer, Ipsen, Novartis, and Novo Nordisk, and served as a Council member for Endocrine Society of Australia. SM has received grants to his institution from US Food and Drug Administration and non-financial support from Cyclacel. MM has received grants to his institution from Corcept, Novartis, and Strongbridge; fees for expert testimony from Janssen and Corcept; and personal honoraria for advisory boards for Merck, Pfizer, Recordati, and Strongbridge. JN-P has received grants and honoraria to the institution for consulting and advisory boards from Diurnal Ltd and HRA Pharma, Recordati, and Novartis; and served as a Board member or advisor for Pituitary Foundation and Endocrine Society. LN has received royalties from UpToDate and support for meeting attendance from the NIH, and has served as a Board member for Endocrine Society. AMP has received grants to his institution from HRA Pharma and served as advisor for European Reference Network on Rare Endocrine Conditions and European Endocrine Society. SP has received personal honoraria for lectures and advisory boards from HRA Pharma, Recordati Pharma, Novartis Pharma, and Crinetics Pharmaceuticals. RP has received grants to his institution from Novartis, Pfizer, Ipsen, Shire, IBSA Farmaceutici, HRA Pharma, Cortendo AB, Corcept Therapeutics, and Merck Serono, and personal honoraria for consulting, lectures, support for meeting attendance, and advisory boards from Novartis, Shire, HRA Pharma, Cortendo AB, Pfizer, Recordati, IBSA Farmaceutici, and Crinetics Pharmaceuticals. HR has received personal honoraria for consulting from Cerium and non-financial support from Corcept. MR has received personal honoraria for consulting, lectures, and advisory boards from Novartis, Recordati, HRA Pharma, and Ipsen. RS has received grants to his institution from Corcept and Crinetics, and personal honoraria for consulting from Strongbridge, Corcept, HRA Pharma, and Sterotherapeutics. CS has received grants and personal honoraria for lectures from Pfizer, Novartis, Recordati Rare Diseases, and HRA Pharma. IS has received personal honoraria for consulting from Medison Pharma. CAS has received grants from Pfizer; personal honoraria for consulting and support for meeting attendance from Lundbeck Pharma and the NIH; holds patents on the genetics of *PRKARIA*, *PDE11A*, and *GPR101*; and has served as a Board member or advisor for Society for Pediatric Research, Children's Inn at NIH, and Cushing's Foundation. AT has received grants to his institution from HRA Pharma, and personal honoraria for consulting, lectures, and support for meeting attendance from HRA Pharma, Recordati Rare Diseases, and Ipsen. YT has received personal honoraria for consulting and lectures from Novo Nordisk, Recordati Rare Diseases, Bohringer Ingelheim, and Sumitomo Dainippon Pharma. MT has served as an advisor to European Society of Endocrinology. ST has received grants to his institution from Strongbridge, Crinetics, and Novartis, and personal honoraria for lectures, advisory boards, and support for meeting attendance from Recordati, Pfizer, and Ipsen. EV has received grants through the European Society of Endocrinology from HRA Pharma, Novartis, Recordati, and Corcept, and received personal honoraria for consulting, lectures, and advisory boards from HRA Pharma, HRA Pharma Spain, and Recordati Rare Diseases. GV has received grants to her institution from Novartis, Recordati, and Corcept; personal honoraria and honoraria to the institution for consulting and lectures from HRA Pharma and Recordati; and served as an advisor for Cushing's Hub. SMW has received grants through the European Society of Endocrinology from HRA Pharma, Novartis, Recordati, and Corcept, and received personal honoraria for consulting and lectures from HRA Pharma and Recordati Rare Diseases. MCZ has served as a Board member for European Neuroendocrine Association. BMKB has received grants to her institution from Novartis, Opko, Strongbridge, and Millendo; personal honoraria for consulting from Aeterna Zentaris, Ascendis, Crinetics, Merck Serono, Novartis, Novo Nordisk, Recordati, Strongbridge, and Sparrow; and served as an advisor for Endocrine Society. MB, KH, PM, BS, EVV, and JW have no competing interests.

Acknowledgments

The authors thank Professors Annamaria Colao, Richard Feelders, and AJ van der Lely for their contributions to the meeting. The authors thank Shira Berman of Cedars-Sinai Medical Center for editorial assistance. Virtual meeting logistics were supported by unrestricted educational grants to the Pituitary Society from Ascendis Pharma, Crinetics Pharmaceuticals, HRA Pharma, Novo Nordisk, Recordati Rare Diseases, and Strongbridge Biopharma. Supporters were invited to observe the highlight summaries presented during the meeting, but did not participate in the small group discussions, had no role in the development of consensus recommendations or topics for future research, and did not review the manuscript prior to publication.

References

- Cushing H. The basophil adenomas of the pituitary body and their clinical manifestation. *Bull Johns Hopkins Hosp* 1932; **50**: 137–95.
- Melmed S. Pituitary-tumor endocrinopathies. *N Engl J Med* 2020; **382**: 937–50.
- Valassi E, Feelders R, Maiter D, et al. Worse health-related quality of life at long-term follow-up in patients with Cushing's disease than patients with cortisol producing adenoma: data from the ERCUSYN. *Clin Endocrinol (Oxf)* 2018; **88**: 787–98.
- Arnaldi G, Angeli A, Atkinson AB, et al. Diagnosis and complications of Cushing's syndrome: a consensus statement. *J Clin Endocrinol Metab* 2003; **88**: 5593–602.
- Nieman LK, Biller BM, Findling JW, et al. The diagnosis of Cushing's syndrome: an Endocrine Society clinical practice guideline. *J Clin Endocrinol Metab* 2008; **93**: 1526–40.
- Biller BM, Grossman AB, Stewart PM, et al. Treatment of adrenocorticotropic-dependent Cushing's syndrome: a consensus statement. *J Clin Endocrinol Metab* 2008; **93**: 2454–62.
- Nieman LK, Biller BM, Findling JW, et al. Treatment of Cushing's syndrome: an Endocrine Society clinical practice guideline. *J Clin Endocrinol Metab* 2015; **100**: 2807–31.
- Guyatt GH, Oxman AD, Vist GE, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ* 2008; **336**: 924–26.
- Giustina A, Chanson P, Kleinberg D, et al. Expert consensus document: A consensus on the medical treatment of acromegaly. *Nat Rev Endocrinol* 2014; **10**: 243–8.
- Rubinstein G, Osswald A, Hoster E, et al. Time to diagnosis in Cushing's syndrome: a meta-analysis based on 5367 patients. *J Clin Endocrinol Metab* 2020; **105**: e12–22.
- Raff H, Carroll T. Cushing's syndrome: from physiological principles to diagnosis and clinical care. *J Physiol* 2015; **593**: 493–506.
- Galm BP, Qiao N, Klibanski A, Biller BMK, Tritos NA. Accuracy of laboratory tests for the diagnosis of Cushing syndrome. *J Clin Endocrinol Metab* 2020; **105**: 2081–94.
- Petersenn S. Biochemical diagnosis of Cushing's disease: screening and confirmatory testing. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101519.
- Putignano P, Toja P, Dubini A, Pecori Giraldo F, Corsello SM, Cavagnini F. Midnight salivary cortisol versus urinary free and midnight serum cortisol as screening tests for Cushing's syndrome. *J Clin Endocrinol Metab* 2003; **88**: 4153–57.
- Raff H. Cushing's syndrome: diagnosis and surveillance using salivary cortisol. *Pituitary* 2012; **15**: 64–70.
- Carroll T, Raff H, Findling JW. Late-night salivary cortisol for the diagnosis of Cushing syndrome: a meta-analysis. *Endocr Pract* 2009; **15**: 335–42.
- Raff H, Phillips JM. Bedtime salivary cortisol and cortisone by LC-MS/MS in healthy adult subjects: evaluation of sampling time. *J Endocr Soc* 2019; **3**: 1631–40.
- Petersenn S. Biochemical diagnosis of Cushing's disease: screening and confirmatory testing. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101519.
- Jahandideh D, Swearingen B, Nachtigall LB, Klibanski A, Biller BMK, Tritos NA. Characterization of cyclic Cushing's disease using late night salivary cortisol testing. *Clin Endocrinol (Oxf)* 2018; **89**: 336–45.
- Debono M, Bradburn M, Bull M, Harrison B, Ross RJ, Newell-Price J. Cortisol as a marker for increased mortality in patients with incidental adrenocortical adenomas. *J Clin Endocrinol Metab* 2014; **99**: 4462–70.
- Ueland GA, Methlie P, Kellmann R, et al. Simultaneous assay of cortisol and dexamethasone improved diagnostic accuracy of the dexamethasone suppression test. *Eur J Endocrinol* 2017; **176**: 705–13.
- Orbach O, Schussler GC. Increased serum cortisol binding in chronic active hepatitis. *Am J Med* 1989; **86**: 39–42.
- Fleseriu M, Hamrahian AH, Hoffman AR, et al. American Association of Clinical Endocrinologists and American College of Endocrinology disease state clinical review: diagnosis of recurrence in Cushing disease. *Endocr Pract* 2016; **22**: 1436–48.
- Ceccato F, Artusi C, Barbot M, et al. Dexamethasone measurement during low-dose suppression test for suspected hypercortisolism: threshold development with and validation. *J Endocrinol Invest* 2020; **43**: 1105–13.
- Roper SM. Yield of serum dexamethasone measurement for reducing false-positive results of low-dose dexamethasone suppression testing. *J Appl Lab Med* 2021; **6**: 480–85.
- Findling JW, Raff H, Aron DC. The low-dose dexamethasone suppression test: a reevaluation in patients with Cushing's syndrome. *J Clin Endocrinol Metab* 2004; **89**: 1222–26.
- Raff H, Auchus RJ, Findling JW, Nieman LK. Urine free cortisol in the diagnosis of Cushing's syndrome: is it worth doing and, if so, how? *J Clin Endocrinol Metab* 2015; **100**: 395–97.
- Petersenn S, Newell-Price J, Findling JW, et al. High variability in baseline urinary free cortisol values in patients with Cushing's disease. *Clin Endocrinol (Oxf)* 2014; **80**: 261–69.
- Chen AX, Haas AV, Williams GH, Vaidya A. Dietary sodium intake and cortisol measurements. *Clin Endocrinol (Oxf)* 2020; **93**: 539–45.
- Moffat SD, An Y, Resnick SM, Diamond MP, Ferrucci L. Longitudinal change in cortisol levels across the adult life span. *J Gerontol A Biol Sci Med Sci* 2020; **75**: 394–400.
- Schorr M, Lawson EA, Dichtel LE, Klibanski A, Miller KK. Cortisol measures across the weight spectrum. *J Clin Endocrinol Metab* 2015; **100**: 3313–21.
- Deutschbein T, Broecker-Preuss M, Hartmann MF, et al. Measurement of urinary free cortisol by current immunoassays: need for sex-dependent reference ranges to define hypercortisolism. *Horm Metab Res* 2011; **43**: 714–19.
- Mericq MV, Cutler GB Jr. High fluid intake increases urine free cortisol excretion in normal subjects. *J Clin Endocrinol Metab* 1998; **83**: 682–84.
- Rosmalen JG, Kema IP, Wust S, et al. 24 h urinary free cortisol in large-scale epidemiological studies: short-term and long-term stability and sources of variability. *Psychoneuroendocrinology* 2014; **47**: 10–16.
- Raff H, Cohen EP, Findling JW. A commentary on diagnosing Cushing's disease in the context of renal failure. *Eur J Endocrinol* 2019; **181**: C9–C11.
- Carroll TB, Findling JW. The diagnosis of Cushing's syndrome. *Rev Endocr Metab Disord* 2010; **11**: 147–53.
- Fukuoka H, Shichi H, Yamamoto M, Takahashi Y. The mechanisms underlying autonomous adrenocorticotropic hormone secretion in Cushing's disease. *Int J Mol Sci* 2020; **21**: 9132.
- Scaroni C, Albiger NM, Palmieri S, et al. Approach to patients with pseudo-Cushing's states. *Endocr Connect* 2020; **9**: R1–13.
- Alwani RA, Schmit Jongbloed LW, de Jong FH, van der Lely AJ, de Herder WW, Feelders RA. Differentiating between Cushing's disease and pseudo-Cushing's syndrome: comparison of four tests. *Eur J Endocrinol* 2014; **170**: 477–86.
- Pecori Giraldo F, Pivonello R, Ambrogio AG, et al. The dexamethasone-suppressed corticotropin-releasing hormone stimulation test and the desmopressin test to distinguish Cushing's syndrome from pseudo-Cushing's states. *Clin Endocrinol (Oxf)* 2007; **66**: 251–57.
- Tirabassi G, Faloia E, Papa R, Furlani G, Boscaro M, Arnaldi G. Use of the desmopressin test in the differential diagnosis of pseudo-Cushing state from Cushing's disease. *J Clin Endocrinol Metab* 2010; **95**: 1115–22.
- Martin NM, Dhillon WS, Banerjee A, et al. Comparison of the dexamethasone-suppressed corticotropin-releasing hormone test and low-dose dexamethasone suppression test in the diagnosis of Cushing's syndrome. *J Clin Endocrinol Metab* 2006; **91**: 2582–86.
- Moro M, Putignano P, Losa M, Invitti C, Maraschini C, Cavagnini F. The desmopressin test in the differential diagnosis between Cushing's disease and pseudo-Cushing states. *J Clin Endocrinol Metab* 2000; **85**: 3569–74.

- 44 Rollin GA, Costenaro F, Gerchman F, Rodrigues TC, Czepielewski MA. Evaluation of the DDAVP test in the diagnosis of Cushing's Disease. *Clin Endocrinol (Oxf)* 2015; **82**: 793–800.
- 45 Tirabassi G, Papa R, Faloia E, Boscaro M, Arnaldi G. Corticotrophin-releasing hormone and desmopressin tests in the differential diagnosis between Cushing's disease and pseudo-Cushing state: a comparative study. *Clin Endocrinol (Oxf)* 2011; **75**: 666–72.
- 46 Ceccato F, Tizianel I, Vedolin CK, Boscaro M, Barbot M, Scaroni C. Human corticotropin-releasing hormone tests: 10 years of real-life experience in pituitary and adrenal disease. *J Clin Endocrinol Metab* 2020; **105**: e3938–49.
- 47 Braun LT, Riestler A, Osswald-Kopp A, et al. Toward a diagnostic score in Cushing's syndrome. *Front Endocrinol (Lausanne)* 2019; **10**: 766.
- 48 Nieman LK. Cushing's syndrome: update on signs, symptoms and biochemical screening. *Eur J Endocrinol* 2015; **173**: M33–38.
- 49 Newell-Price J, Nieman LK, Reincke M, Tabarin A. Endocrinology in the time of COVID-19: management of Cushing's syndrome. *Eur J Endocrinol* 2020; **183**: G1–7.
- 50 Fleseriu M, Buchfelder M, Cetas JS, et al. Pituitary Society guidance: pituitary disease management and patient care recommendations during the COVID-19 pandemic—an international perspective. *Pituitary* 2020; **23**: 327–37.
- 51 Yanovski JA, Cutler GB Jr, Doppman JL, et al. The limited ability of inferior petrosal sinus sampling with corticotropin-releasing hormone to distinguish Cushing's disease from pseudo-Cushing states or normal physiology. *J Clin Endocrinol Metab* 1993; **77**: 503–09.
- 52 Alexandraki KI, Kaltsas GA, Isidori AM, et al. The prevalence and characteristic features of cyclicity and variability in Cushing's disease. *Eur J Endocrinol* 2009; **160**: 1011–18.
- 53 Findling JW, Raff H. Diagnosis of endocrine disease: differentiation of pathologic/neoplastic hypercortisolism (Cushing's syndrome) from physiologic/non-neoplastic hypercortisolism (formerly known as pseudo-Cushing's syndrome). *Eur J Endocrinol* 2017; **176**: R205–16.
- 54 Valassi E, Swearingen B, Lee H, et al. Concomitant medication use can confound interpretation of the combined dexamethasone-corticotropin releasing hormone test in Cushing's syndrome. *J Clin Endocrinol Metab* 2009; **94**: 4851–59.
- 55 Buchfelder M, Nistor R, Fahlbusch R, Huk WJ. The accuracy of CT and MR evaluation of the sella turcica for detection of adrenocorticotropic hormone-secreting adenomas in Cushing disease. *AJNR Am J Neuroradiol* 1993; **14**: 1183–90.
- 56 Chatain GP, Patronas N, Smirniotopoulos JG, et al. Potential utility of FLAIR in MRI-negative Cushing's disease. *J Neurosurg* 2018; **129**: 620–28.
- 57 Portocarrero-Ortiz L, Bonifacio-Delgadillo D, Sotomayor-Gonzalez A, Garcia-Marquez A, Lopez-Serna R. A modified protocol using half-dose gadolinium in dynamic 3-Tesla magnetic resonance imaging for detection of ACTH-secreting pituitary tumors. *Pituitary* 2010; **13**: 230–35.
- 58 Patel V, Liu CJ, Shiroishi MS, et al. Ultra-high field magnetic resonance imaging for localization of corticotropin-secreting pituitary adenomas. *Neuroradiology* 2020; **62**: 1051–54.
- 59 Chowdhury IN, Sinaii N, Oldfield EH, Patronas N, Nieman LK. A change in pituitary magnetic resonance imaging protocol detects ACTH-secreting tumours in patients with previously negative results. *Clin Endocrinol (Oxf)* 2010; **72**: 502–06.
- 60 MacFarlane J, Bashari WA, Senanayake R, et al. Advances in the imaging of pituitary tumors. *Endocrinol Metab Clin North Am* 2020; **49**: 357–73.
- 61 Grober Y, Grober H, Wintermark M, Jane JA, Oldfield EH. Comparison of MRI techniques for detecting microadenomas in Cushing's disease. *J Neurosurg* 2018; **128**: 1051–57.
- 62 Mathioudakis N, Pendleton C, Quinones-Hinojosa A, Wand GS, Salvatori R. ACTH-secreting pituitary adenomas: size does not correlate with hormonal activity. *Pituitary* 2012; **15**: 526–32.
- 63 Alzahrani AS, Farhat R, Al-Arifi A, Al-Kahtani N, Kanaan I, Abouzied M. The diagnostic value of fused positron emission tomography/computed tomography in the localization of adrenocorticotropic-secreting pituitary adenoma in Cushing's disease. *Pituitary* 2009; **12**: 309–14.
- 64 Chittiboyna P, Montgomery BK, Millo C, Herscovitch P, Lonser RR. High-resolution ¹⁸F-fluorodeoxyglucose positron emission tomography and magnetic resonance imaging for pituitary adenoma detection in Cushing disease. *J Neurosurg* 2015; **122**: 791–97.
- 65 Boyle J, Patronas NJ, Smirniotopoulos J, et al. CRH stimulation improves ¹⁸F-FDG-PET detection of pituitary adenomas in Cushing's disease. *Endocrine* 2019; **65**: 155–65.
- 66 Ikeda H, Abe T, Watanabe K. Usefulness of composite methionine-positron emission tomography/3.0-tesla magnetic resonance imaging to detect the localization and extent of early-stage Cushing adenoma. *J Neurosurg* 2010; **112**: 750–55.
- 67 Koulouri O, Steuwe A, Gillett D, et al. A role for ¹¹C-methionine PET imaging in ACTH-dependent Cushing's syndrome. *Eur J Endocrinol* 2015; **173**: M107–20.
- 68 Walia R, Gupta R, Bhansali A, et al. Molecular imaging targeting corticotropin-releasing hormone receptor for corticotropinoma: a changing paradigm. *J Clin Endocrinol Metab* 2021; **106**: e1816–26.
- 69 Newell-Price J, Perry L, Medbak S, et al. A combined test using desmopressin and corticotropin-releasing hormone in the differential diagnosis of Cushing's syndrome. *J Clin Endocrinol Metab* 1997; **82**: 176–81.
- 70 Vassiliadi DA, Tsagarakis S. Diagnosis of endocrine disease: the role of the desmopressin test in the diagnosis and follow-up of Cushing's syndrome. *Eur J Endocrinol* 2018; **178**: R201–14.
- 71 Lacroix A, Feelders RA, Stratakis CA, Nieman LK. Cushing's syndrome. *Lancet* 2015; **386**: 913–27.
- 72 Messenger M, Carriere C, Bertagna X, de Keyser Y. RT-PCR analysis of corticotroph-associated genes expression in carcinoid tumours in the ectopic-ACTH syndrome. *Eur J Endocrinol* 2006; **154**: 159–66.
- 73 Tsagarakis S, Tsigos C, Vasiliou V, et al. The desmopressin and combined CRH-desmopressin tests in the differential diagnosis of ACTH-dependent Cushing's syndrome: constraints imposed by the expression of V2 vasopressin receptors in tumors with ectopic ACTH secretion. *J Clin Endocrinol Metab* 2002; **87**: 1646–53.
- 74 Ritzel K, Beuschlein F, Berr C, et al. ACTH after 15 min distinguishes between Cushing's disease and ectopic Cushing's syndrome: a proposal for a short and simple CRH test. *Eur J Endocrinol* 2015; **173**: 197–204.
- 75 Reimondo G, Paccotti P, Minetto M, et al. The corticotrophin-releasing hormone test is the most reliable noninvasive method to differentiate pituitary from ectopic ACTH secretion in Cushing's syndrome. *Clin Endocrinol (Oxf)* 2003; **58**: 718–24.
- 76 Newell-Price J, Morris DG, Drake WM, et al. Optimal response criteria for the human CRH test in the differential diagnosis of ACTH-dependent Cushing's syndrome. *J Clin Endocrinol Metab* 2002; **87**: 1640–45.
- 77 Barbot M, Trementino L, Zilio M, et al. Second-line tests in the differential diagnosis of ACTH-dependent Cushing's syndrome. *Pituitary* 2016; **19**: 488–95.
- 78 Oldfield EH, Chrousos GP, Schulte HM, et al. Preoperative lateralization of ACTH-secreting pituitary microadenomas by bilateral and simultaneous inferior petrosal venous sinus sampling. *N Engl J Med* 1985; **312**: 100–03.
- 79 Loriaux DL. Diagnosis and differential diagnosis of Cushing's syndrome. *N Engl J Med* 2017; **376**: 1451–59.
- 80 Sharma ST, Raff H, Nieman LK. Prolactin as a marker of successful catheterization during IPSS in patients with ACTH-dependent Cushing's syndrome. *J Clin Endocrinol Metab* 2011; **96**: 3687–94.
- 81 Frete C, Corcuff JB, Kuhn E, et al. Non-invasive diagnostic strategy in ACTH-dependent Cushing's syndrome. *J Clin Endocrinol Metab* 2020; **105**: 3273–84.
- 82 Nieman LK. Is it time for a new approach to the differential diagnosis of ACTH-dependent Cushing syndrome? *J Clin Endocrinol Metab* 2020; **105**: e4964–66.
- 83 Hofman MS, Lau WF, Hicks RJ. Somatostatin receptor imaging with ⁶⁸Ga-DOTATATE PET/CT: clinical utility, normal patterns, pearls, and pitfalls in interpretation. *Radiographics* 2015; **35**: 500–16.
- 84 Varlamov E, Hinojosa-Amaya JM, Stack M, Fleseriu M. Diagnostic utility of Gallium-68-somatostatin receptor PET/CT in ectopic ACTH-secreting tumors: a systematic literature review and single-center clinical experience. *Pituitary* 2019; **22**: 445–55.
- 85 Deppen SA, Blume J, Bobbey AJ, et al. ⁶⁸Ga-DOTATATE compared with ¹¹¹In-DTPA-octreotide and conventional imaging for pulmonary and gastroenteropancreatic neuroendocrine tumors: a systematic review and meta-analysis. *J Nucl Med* 2016; **57**: 872–78.

- 86 Isidori AM, Sbardella E, Zatelli MC, et al. Conventional and nuclear medicine imaging in ectopic Cushing's syndrome: a systematic review. *J Clin Endocrinol Metab* 2015; **100**: 3231–44.
- 87 Wannachalee T, Turcu AF, Bancos I, et al. The clinical impact of [⁶⁸Ga]-DOTATATE PET/CT for the diagnosis and management of ectopic adrenocorticotrophic hormone - secreting tumours. *Clin Endocrinol (Oxf)* 2019; **91**: 288–94.
- 88 Senanayake R, Gillett D, MacFarlane J, et al. New types of localization methods for adrenocorticotrophic hormone-dependent Cushing's syndrome. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101513.
- 89 Isidori AM, Kaltsas GA, Mohammed S, et al. Discriminatory value of the low-dose dexamethasone suppression test in establishing the diagnosis and differential diagnosis of Cushing's syndrome. *J Clin Endocrinol Metab* 2003; **88**: 5299–306.
- 90 van der Pas R, de Bruin C, Leebeek FW, et al. The hypercoagulable state in Cushing's disease is associated with increased levels of procoagulant factors and impaired fibrinolysis, but is not reversible after short-term biochemical remission induced by medical therapy. *J Clin Endocrinol Metab* 2012; **97**: 1303–10.
- 91 Van Zaane B, Nur E, Squizzato A, et al. Hypercoagulable state in Cushing's syndrome: a systematic review. *J Clin Endocrinol Metab* 2009; **94**: 2743–50.
- 92 Wagner J, Langlois F, Lim DST, McCartney S, Fleseriu M. Hypercoagulability and risk of venous thromboembolic events in endogenous Cushing's syndrome: a systematic meta-analysis. *Front Endocrinol (Lausanne)* 2018; **9**: 805.
- 93 Coelho MC, Vieira Neto L, Kasuki L, et al. Rotation thrombelastometry and the hypercoagulable state in Cushing's syndrome. *Clin Endocrinol (Oxf)* 2014; **81**: 657–64.
- 94 Stuijver DJ, van Zaane B, Feelders RA, et al. Incidence of venous thromboembolism in patients with Cushing's syndrome: a multicenter cohort study. *J Clin Endocrinol Metab* 2011; **96**: 3525–32.
- 95 Suarez MG, Stack M, Hinojosa-Amaya JM, et al. Hypercoagulability in Cushing syndrome, prevalence of thrombotic events: a large, single-center, retrospective study. *J Endocr Soc* 2020; **4**: bvz033.
- 96 Babic B, De Roulet A, Volpe A, Nilubol N. Is VTE prophylaxis necessary on discharge for patients undergoing adrenalectomy for Cushing syndrome? *J Endocr Soc* 2019; **3**: 304–13.
- 97 Barbot M, Guarnotta V, Zilio M, et al. Effects of pasireotide treatment on coagulative profile: a prospective study in patients with Cushing's disease. *Endocrine* 2018; **62**: 207–14.
- 98 Boscaro M, Sonino N, Scarda A, et al. Anticoagulant prophylaxis markedly reduces thromboembolic complications in Cushing's syndrome. *J Clin Endocrinol Metab* 2002; **87**: 3662–66.
- 99 Barbot M, Daidone V, Zilio M, et al. Perioperative thromboprophylaxis in Cushing's disease: what we did and what we are doing? *Pituitary* 2015; **18**: 487–93.
- 100 Fleseriu M, Biller B, Grossman A, et al, on behalf of the Pituitary Society International Cushing Disease Workshop Task Force. Hypercoagulability in Cushing disease: a risk awareness and prophylaxis survey on behalf of the Pituitary Society. 15th International Pituitary Congress; Orlando, FL; March 29–31, 2017 (abstr P7).
- 101 Zilio M, Mazza L, Sartori MT, et al. A venous thromboembolism risk assessment model for patients with Cushing's syndrome. *Endocrine* 2016; **52**: 322–32.
- 102 Pivonello R, Isidori AM, De Martino MC, Newell-Price J, Biller BM, Colao A. Complications of Cushing's syndrome: state of the art. *Lancet Diabetes Endocrinol* 2016; **4**: 611–29.
- 103 Ntali G, Asimakopoulou A, Siamatras T, et al. Mortality in Cushing's syndrome: systematic analysis of a large series with prolonged follow-up. *Eur J Endocrinol* 2013; **169**: 715–23.
- 104 Roldan-Sarmiento P, Lam-Chung CE, Hinojosa-Amaya JM, et al. Diabetes, active disease, and afternoon serum cortisol levels predict Cushing's disease mortality: a cohort study. *J Clin Endocrinol Metab* 2021; **106**: e103–11.
- 105 Scherthaner-Reiter MH, Siess C, Micko A, et al. Acute and life-threatening complications in Cushing syndrome: prevalence, predictors, and mortality. *J Clin Endocrinol Metab* 2021; **106**: e2035–46.
- 106 Geer EB, Shen W, Strohmayer E, Post KD, Freda PU. Body composition and cardiovascular risk markers after remission of Cushing's disease: a prospective study using whole-body MRI. *J Clin Endocrinol Metab* 2012; **97**: 1702–11.
- 107 Giordano R, Picu A, Marinazzo E, et al. Metabolic and cardiovascular outcomes in patients with Cushing's syndrome of different aetiologies during active disease and 1 year after remission. *Clin Endocrinol (Oxf)* 2011; **75**: 354–60.
- 108 Toja PM, Branzi G, Ciambellotti F, et al. Clinical relevance of cardiac structure and function abnormalities in patients with Cushing's syndrome before and after cure. *Clin Endocrinol (Oxf)* 2012; **76**: 332–38.
- 109 Dekkers OM, Horvath-Puho E, Jorgensen JO, et al. Multisystem morbidity and mortality in Cushing's syndrome: a cohort study. *J Clin Endocrinol Metab* 2013; **98**: 2277–84.
- 110 Papakokkinou E, Olsson DS, Chantzichristos D, et al. Excess morbidity persists in patients with Cushing's disease during long-term remission: a Swedish nationwide study. *J Clin Endocrinol Metab* 2020; **105**: 2616–24.
- 111 Ntali G, Hakami O, Wattedgama M, Ahmed S, Karavitaki N. Mortality of patients with Cushing's disease. *Exp Clin Endocrinol Diabetes* 2021; **129**: 203–07.
- 112 Ragnarsson O, Olsson DS, Papakokkinou E, et al. Overall and disease-specific mortality in patients with Cushing disease: a Swedish nationwide study. *J Clin Endocrinol Metab* 2019; **104**: 2375–84.
- 113 Clayton RN, Jones PW, Reulen RC, et al. Mortality in patients with Cushing's disease more than 10 years after remission: a multicentre, multinational, retrospective cohort study. *Lancet Diabetes Endocrinol* 2016; **4**: 569–76.
- 114 Varlamov EV, Langlois F, Vila G, Fleseriu M. Cardiovascular risk assessment, thromboembolism and infection prevention in Cushing's syndrome—a practical approach. *Eur J Endocrinol* 2021; **184**: R207–224.
- 115 Mazziotti G, Frara S, Giustina A. Pituitary diseases and bone. *Endocr Rev* 2018; **39**: 440–88.
- 116 Braun LT, Fazel J, Zopp S, et al. The effect of biochemical remission on bone metabolism in Cushing's syndrome: a 2-year follow-up study. *J Bone Miner Res* 2020; **35**: 1711–17.
- 117 Scillitani A, Mazziotti G, Di Somma C, et al. Treatment of skeletal impairment in patients with endogenous hypercortisolism: when and how? *Osteoporos Int* 2014; **25**: 441–46.
- 118 Di Somma C, Colao A, Pivonello R, et al. Effectiveness of chronic treatment with alendronate in the osteoporosis of Cushing's disease. *Clin Endocrinol (Oxf)* 1998; **48**: 655–62.
- 119 Mazziotti G, Giustina A. Glucocorticoids and the regulation of growth hormone secretion. *Nat Rev Endocrinol* 2013; **9**: 265–76.
- 120 Tritos NA. Growth hormone deficiency in adults with Cushing's disease. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101474.
- 121 Tzanela M, Karavitaki N, Stylianidou C, Tsagarakis S, Thalassinou NC. Assessment of GH reserve before and after successful treatment of adult patients with Cushing's syndrome. *Clin Endocrinol (Oxf)* 2004; **60**: 309–14.
- 122 Formenti AM, Maffezzoni F, Doga M, Mazziotti G, Giustina A. Growth hormone deficiency in treated acromegaly and active Cushing's syndrome. *Best Pract Res Clin Endocrinol Metab* 2017; **31**: 79–90.
- 123 Hughes NR, Lissett CA, Shalet SM. Growth hormone status following treatment for Cushing's syndrome. *Clin Endocrinol (Oxf)* 1999; **51**: 61–66.
- 124 Pecori Giraldi F, Andrioli M, De Marinis L, et al. Significant GH deficiency after long-term cure by surgery in adult patients with Cushing's disease. *Eur J Endocrinol* 2007; **156**: 233–39.
- 125 Feldt-Rasmussen U, Abs R, Bengtsson BA, et al. Growth hormone deficiency and replacement in hypopituitary patients previously treated for acromegaly or Cushing's disease. *Eur J Endocrinol* 2002; **146**: 67–74.
- 126 Webb SM, Mo D, Lamberts SW, et al. Metabolic, cardiovascular, and cerebrovascular outcomes in growth hormone-deficient subjects with previous Cushing's disease or non-functioning pituitary adenoma. *J Clin Endocrinol Metab* 2010; **95**: 630–38.
- 127 Hoybye C, Ragnarsson O, Jonsson PJ, et al. Clinical features of GH deficiency and effects of 3 years of GH replacement in adults with controlled Cushing's disease. *Eur J Endocrinol* 2010; **162**: 677–84.
- 128 Vogel F, Braun L, Rubinstein G, et al. Patients with low IGF-I after curative surgery for Cushing's syndrome have an adverse long-term outcome of hypercortisolism-induced myopathy. *Eur J Endocrinol* 2021; **184**: 813–21.

- 129 Colson A, Brooke AM, Walker D, et al. Growth hormone deficiency and replacement in patients with treated Cushing's disease, prolactinomas and non-functioning pituitary adenomas: effects on body composition, glucose metabolism, lipid status and bone mineral density. *Horm Res* 2006; **66**: 257–67.
- 130 Johannsson G, Sunnerhagen KS, Svensson J. Baseline characteristics and the effects of two years of growth hormone replacement therapy in adults with growth hormone deficiency previously treated for Cushing's disease. *Clin Endocrinol (Oxf)* 2004; **60**: 550–59.
- 131 Ragnarsson O, Hoybye C, Jonsson PJ, et al. Comorbidity and cardiovascular risk factors in adult GH deficiency following treatment for Cushing's disease or non-functioning pituitary adenomas during childhood. *Eur J Endocrinol* 2012; **166**: 593–600.
- 132 Shekhar S, McGlotten R, Auh S, Rother KI, Nieman LK. The hypothalamic-pituitary-thyroid axis in Cushing syndrome before and after curative surgery. *J Clin Endocrinol Metab* 2021; **106**: e1316–31.
- 133 McBride M, Crespo I, Webb SM, Valassi E. Quality of life in Cushing's syndrome. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101505.
- 134 Vogel F, Braun LT, Rubinstein G, et al. Persisting muscle dysfunction in Cushing's syndrome despite biochemical remission. *J Clin Endocrinol Metab* 2020; **105**: e4490–98.
- 135 Reincke M. Cushing syndrome associated myopathy: it is time for a change. *Endocrinol Metab (Seoul)* 2021; **36**: 564–71.
- 136 Fleseriu M, Hashim IA, Karavitaki N, et al. Hormonal replacement in hypopituitarism in adults: an Endocrine Society clinical practice guideline. *J Clin Endocrinol Metab* 2016; **101**: 3888–921.
- 137 Alexandraki KI, Kaltsas GA, Isidori AM, et al. Long-term remission and recurrence rates in Cushing's disease: predictive factors in a single-centre study. *Eur J Endocrinol* 2013; **168**: 639–48.
- 138 Ciric I, Zhao JC, Du H, et al. Transsphenoidal surgery for Cushing disease: experience with 136 patients. *Neurosurgery* 2012; **70**: 70–81.
- 139 Capatina C, Hinojosa-Amaya JM, Poiana C, Fleseriu M. Management of patients with persistent or recurrent Cushing's disease after initial pituitary surgery. *Expert Rev Endocrinol Metab* 2020; **15**: 321–39.
- 140 Stroud A, Dhaliwal P, Alvarado R, et al. Outcomes of pituitary surgery for Cushing's disease: a systematic review and meta-analysis. *Pituitary* 2020; **23**: 595–609.
- 141 Valassi E, Biller BM, Swearingen B, et al. Delayed remission after transsphenoidal surgery in patients with Cushing's disease. *J Clin Endocrinol Metab* 2010; **95**: 601–10.
- 142 Fan Y, Li Y, Bao X, et al. Development of machine learning models for predicting postoperative delayed remission of patients with Cushing's disease. *J Clin Endocrinol Metab* 2021; **106**: e217–31.
- 143 Petersenn S, Beckers A, Ferone D, et al. Therapy of endocrine disease: outcomes in patients with Cushing's disease undergoing transsphenoidal surgery: systematic review assessing criteria used to define remission and recurrence. *Eur J Endocrinol* 2015; **172**: R227–39.
- 144 Broersen LHA, Biermasz NR, van Furth WR, et al. Endoscopic vs microscopic transsphenoidal surgery for Cushing's disease: a systematic review and meta-analysis. *Pituitary* 2018; **21**: 524–34.
- 145 Hattori Y, Tahara S, Aso S, et al. Pituitary surgery's epidemiology using a national inpatient database in Japan. *Acta Neurochir (Wien)* 2020; **162**: 1317–23.
- 146 Honegger J, Grimm F. The experience with transsphenoidal surgery and its importance to outcomes. *Pituitary* 2018; **21**: 545–55.
- 147 de Vries F, Lobatto DJ, Versteegen MJT, et al. Outcome squares integrating efficacy and safety, as applied to functioning pituitary adenoma surgery. *J Clin Endocrinol Metab* 2021; **106**: e3300–11.
- 148 Ciric I, Ragin A, Baumgartner C, Pierce D. Complications of transsphenoidal surgery: results of a national survey, review of the literature, and personal experience. *Neurosurgery* 1997; **40**: 225–37.
- 149 Mortini P, Nocera G, Roncelli F, Losa M, Formenti AM, Giustina A. The optimal numerosity of the referral population of pituitary tumors centers of excellence (PTCOE): a surgical perspective. *Rev Endocr Metab Disord* 2020; **21**: 527–36.
- 150 Mortini P, Losa M, Barzaghi R, Boari N, Giovanelli M. Results of transsphenoidal surgery in a large series of patients with pituitary adenoma. *Neurosurgery* 2005; **56**: 1222–33.
- 151 Barker FG 2nd, Curry WT Jr, Carter BS. Surgery for primary supratentorial brain tumors in the United States, 1988 to 2000: the effect of provider caseload and centralization of care. *Neuro Oncol* 2005; **7**: 49–63.
- 152 Casanueva FF, Barkan AL, Buchfelder M, et al. Criteria for the definition of Pituitary Tumor Centers of Excellence (PTCOE): a Pituitary Society statement. *Pituitary* 2017; **20**: 489–98.
- 153 Pendharkar AV, Sussman ES, Ho AL, Hayden Gephart MG, Katznelson L. Cushing's disease: predicting long-term remission after surgical treatment. *Neurosurg Focus* 2015; **38**: E13.
- 154 Patil CG, Prevedello DM, Lad SP, et al. Late recurrences of Cushing's disease after initial successful transsphenoidal surgery. *J Clin Endocrinol Metab* 2008; **93**: 358–62.
- 155 Hofmann BM, Hlavac M, Martinez R, Buchfelder M, Muller OA, Fahlbusch R. Long-term results after microsurgery for Cushing disease: experience with 426 primary operations over 35 years. *J Neurosurg* 2008; **108**: 9–18.
- 156 Mortini P, Barzaghi LR, Albano L, Panni P, Losa M. Microsurgical therapy of pituitary adenomas. *Endocrine* 2018; **59**: 72–81.
- 157 Braun LT, Rubinstein G, Zopp S, et al. Recurrence after pituitary surgery in adult Cushing's disease: a systematic review on diagnosis and treatment. *Endocrine* 2020; **70**: 218–31.
- 158 Hinojosa-Amaya JM, Varlamov EV, McCartney S, Fleseriu M. Hypercortisolemia recurrence in Cushing's disease; a diagnostic challenge. *Front Endocrinol (Lausanne)* 2019; **10**: 740.
- 159 Valero R, Vallette-Kasic S, Conte-Devolx B, Jaquet P, Brue T. The desmopressin test as a predictive factor of outcome after pituitary surgery for Cushing's disease. *Eur J Endocrinol* 2004; **151**: 727–33.
- 160 Le Marc'hadour P, Muller M, Albarel F, et al. Postoperative follow-up of Cushing's disease using cortisol, desmopressin and coupled dexamethasone-desmopressin tests: a head-to-head comparison. *Clin Endocrinol (Oxf)* 2015; **83**: 216–22.
- 161 Lindsay JR, Oldfield EH, Stratakis CA, Nieman LK. The postoperative basal cortisol and CRH tests for prediction of long-term remission from Cushing's disease after transsphenoidal surgery. *J Clin Endocrinol Metab* 2011; **96**: 2057–64.
- 162 Castinetti F, Martinie M, Morange I, et al. A combined dexamethasone desmopressin test as an early marker of postsurgical recurrence in Cushing's disease. *J Clin Endocrinol Metab* 2009; **94**: 1897–903.
- 163 Ambrogio AG, Andrioli M, De Martin M, Cavagnini F, Pecori Giraldi F. Usefulness of desmopressin testing to predict relapse during long-term follow-up in patients in remission from Cushing's disease. *Endocr Connect* 2017; **6**: 791–99.
- 164 Vassiliadi DA, Balomenaki M, Asimakopoulou A, Botoula E, Tzanela M, Tsagarakis S. The desmopressin test predicts better than basal cortisol the long-term surgical outcome of Cushing's disease. *J Clin Endocrinol Metab* 2016; **101**: 4878–85.
- 165 Cambos S, Mohammedi K, Castinetti F, et al. Persistent cortisol response to desmopressin predicts recurrence of Cushing's disease in patients with post-operative corticotropin insufficiency. *Eur J Endocrinol* 2020; **182**: 489–98.
- 166 Amlashi FG, Swearingen B, Faje AT, et al. Accuracy of late-night salivary cortisol in evaluating postoperative remission and recurrence in Cushing's disease. *J Clin Endocrinol Metab* 2015; **100**: 3770–77.
- 167 Carroll TB, Javorsky BR, Findling JW. Postsurgical recurrent Cushing disease: clinical benefit of early intervention in patients with normal urinary free cortisol. *Endocr Pract* 2016; **22**: 1216–23.
- 168 Bou Khalil R, Baudry C, Guignat L, et al. Sequential hormonal changes in 21 patients with recurrent Cushing's disease after successful pituitary surgery. *Eur J Endocrinol* 2011; **165**: 729–37.
- 169 Sandouk Z, Johnston P, Bunch D, et al. Variability of late-night salivary cortisol in Cushing disease: a prospective study. *J Clin Endocrinol Metab* 2018; **103**: 983–90.
- 170 Danet-Lamasou M, Asselineau J, Perez P, et al. Accuracy of repeated measurements of late-night salivary cortisol to screen for early-stage recurrence of Cushing's disease following pituitary surgery. *Clin Endocrinol (Oxf)* 2015; **82**: 260–66.
- 171 Geer EB, Shafiq I, Gordon MB, et al. Biochemical control during long-term follow-up of 230 adult patients with Cushing disease: a multicenter retrospective study. *Endocr Pract* 2017; **23**: 962–70.

- 172 Geer EB, Ayala A, Bonert V, et al. Follow-up intervals in patients with Cushing's disease: recommendations from a panel of experienced pituitary clinicians. *Pituitary* 2017; **20**: 422–29.
- 173 Locatelli M, Vance ML, Laws ER. Clinical review: the strategy of immediate reoperation for transsphenoidal surgery for Cushing's disease. *J Clin Endocrinol Metab* 2005; **90**: 5478–82.
- 174 Rutkowski MJ, Flanigan PM, Aghi MK. Update on the management of recurrent Cushing's disease. *Neurosurg Focus* 2015; **38**: E16.
- 175 Patil CG, Veeravagu A, Prevedello DM, Katznelson L, Vance ML, Laws ER Jr. Outcomes after repeat transsphenoidal surgery for recurrent Cushing's disease. *Neurosurgery* 2008; **63**: 266–70.
- 176 Ram Z, Nieman LK, Cutler GB Jr, Chrousos GP, Doppman JL, Oldfield EH. Early repeat surgery for persistent Cushing's disease. *J Neurosurg* 1994; **80**: 37–45.
- 177 Hameed N, Yedinak CG, Brzana J, et al. Remission rate after transsphenoidal surgery in patients with pathologically confirmed Cushing's disease, the role of cortisol, ACTH assessment and immediate reoperation: a large single center experience. *Pituitary* 2013; **16**: 452–58.
- 178 Cuevas-Ramos D, Fleseriu M. Treatment of Cushing's disease: a mechanistic update. *J Endocrinol* 2014; **223**: R19–39.
- 179 Pivonello R, De Leo M, Cozzolino A, Colao A. The treatment of Cushing's disease. *Endocr Rev* 2015; **36**: 385–486.
- 180 Tritos NA, Biller BMK. Advances in the medical treatment of Cushing disease. *Endocrinol Metab Clin North Am* 2020; **49**: 401–12.
- 181 Pivonello R, Ferrigno R, De Martino MC, et al. Medical treatment of Cushing's disease: an overview of the current and recent clinical trials. *Front Endocrinol (Lausanne)* 2020; **11**: 648.
- 182 Castinetti F, Nieman LK, Reincke M, Newell-Price J. Approach to the patient treated with steroidogenesis inhibitors. *J Clin Endocrinol Metab* 2021; **106**: 2114–23.
- 183 Varlamov EV, Han AJ, Fleseriu M. Updates in adrenal steroidogenesis inhibitors for Cushing's syndrome—a practical guide. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101490.
- 184 Feelders RA, Hofland LJ, de Herder WW. Medical treatment of Cushing's syndrome: adrenal-blocking drugs and ketoconazole. *Neuroendocrinology* 2010; **92** (suppl 1): 111–15.
- 185 Castinetti F, Guignat L, Giraud P, et al. Ketoconazole in Cushing's disease: is it worth a try? *J Clin Endocrinol Metab* 2014; **99**: 1623–30.
- 186 Young J, Bertherat J, Vantyghem MC, et al. Hepatic safety of ketoconazole in Cushing's syndrome: results of a compassionate use programme in France. *Eur J Endocrinol* 2018; **178**: 447–58.
- 187 Hinojosa-Amaya JM, Cuevas-Ramos D, Fleseriu M. Medical management of Cushing's syndrome: current and emerging treatments. *Drugs* 2019; **79**: 935–56.
- 188 Bertagna X, Pivonello R, Fleseriu M, et al. LCI699, a potent 11 β -hydroxylase inhibitor, normalizes urinary cortisol in patients with Cushing's disease: results from a multicenter, proof-of-concept study. *J Clin Endocrinol Metab* 2014; **99**: 1375–83.
- 189 Fleseriu M, Pivonello R, Young J, et al. Osilodrostat, a potent oral 11 β -hydroxylase inhibitor: 22-week, prospective, phase II study in Cushing's disease. *Pituitary* 2016; **19**: 138–48.
- 190 Tanaka T, Satoh F, Ujihara M, et al. A multicenter, phase 2 study to evaluate the efficacy and safety of osilodrostat, a new 11 β -hydroxylase inhibitor, in Japanese patients with endogenous Cushing's syndrome other than Cushing's disease. *Endocr J* 2020; **67**: 841–52.
- 191 Pivonello R, Fleseriu M, Newell-Price J, et al. Efficacy and safety of osilodrostat in patients with Cushing's disease (LINC 3): a multicenter phase III study with a double-blind, randomised withdrawal phase. *Lancet Diabetes Endocrinol* 2020; **8**: 748–61.
- 192 Gadelma M, Bex M, Feelders R, et al. Osilodrostat is an effective and well-tolerated treatment for Cushing's disease: results from a phase III study with an upfront, randomized, double-blind, placebo-controlled phase (LINC 4). 2021 Virtual Meeting of the Endocrine Society (ENDO 2021); March 20–23, 2021 (abstr OR14-1).
- 193 Daniel E, Aylwin S, Mustafa O, et al. Effectiveness of metyrapone in treating Cushing's syndrome: a retrospective multicenter study in 195 patients. *J Clin Endocrinol Metab* 2015; **100**: 4146–54.
- 194 Ceccato F, Zilio M, Barbot M, et al. Metyrapone treatment in Cushing's syndrome: a real-life study. *Endocrine* 2018; **62**: 701–11.
- 195 Krasowski MD, Drees D, Morris CS, Maakestad J, Blau JL, Ekins S. Cross-reactivity of steroid hormone immunoassays: clinical significance and two-dimensional molecular similarity prediction. *BMC Clin Pathol* 2014; **14**: 33.
- 196 Nieman L, Boscaro M, Scaroni C, et al. Metyrapone treatment in endogenous Cushing's syndrome: results at week 12 from PROMPT, a prospective international multicenter, open-label, phase III/IV study. 2021 Virtual Meeting of the Endocrine Society (ENDO 2021); March 20–23, 2021 (abstr OR14-2).
- 197 Kamenicky P, Droumaguet C, Salenave S, et al. Mitotane, metyrapone, and ketoconazole combination therapy as an alternative to rescue adrenalectomy for severe ACTH-dependent Cushing's syndrome. *J Clin Endocrinol Metab* 2011; **96**: 2796–804.
- 198 Baudry C, Coste J, Bou Khalil R, et al. Efficiency and tolerance of mitotane in Cushing's disease in 76 patients from a single center. *Eur J Endocrinol* 2012; **167**: 473–81.
- 199 Carroll TB, Peppard WJ, Herrmann DJ, et al. Continuous etomidate infusion for the management of severe Cushing syndrome: validation of a standard protocol. *J Endocr Soc* 2018; **3**: 1–12.
- 200 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**: 137–43.
- 201 Constantinescu SM, Driessens N, Lefebvre A, Furnica RM, Corvilain B, Maiter D. Etomidate infusion at low doses is an effective and safe treatment for severe Cushing's syndrome outside intensive care. *Eur J Endocrinol* 2020; **183**: 161–67.
- 202 Fleseriu M, Pivonello R, Elenkova A, et al. Efficacy and safety of levoketoconazole in the treatment of endogenous Cushing's syndrome (SONICS): a phase 3, multicentre, open-label, single-arm trial. *Lancet Diabetes Endocrinol* 2019; **7**: 855–65.
- 203 Zacharieva S, Pivonello R, Elenkova A, et al. Safety and efficacy of levoketoconazole in the treatment of endogenous Cushing's syndrome (LOGICS): results from a double-blind, placebo-controlled, randomized withdrawal study. 2021 Virtual Meeting of the Endocrine Society (ENDO 2021); March 20–23, 2021 (abstr P30-1).
- 204 Colao A, Petersenn S, Newell-Price J, et al. A 12-month phase 3 study of pasireotide in Cushing's disease. *N Engl J Med* 2012; **366**: 914–24.
- 205 Pivonello R, Petersenn S, Newell-Price J, et al. Pasireotide treatment significantly improves clinical signs and symptoms in patients with Cushing's disease: results from a phase III study. *Clin Endocrinol (Oxf)* 2014; **81**: 408–17.
- 206 Petersenn S, Salgado LR, Schopohl J, et al. Long-term treatment of Cushing's disease with pasireotide: 5-year results from an open-label extension study of a phase III trial. *Endocrine* 2017; **57**: 156–65.
- 207 Lacroix A, Gu F, Gallardo W, et al. Efficacy and safety of once-monthly pasireotide in Cushing's disease: a 12 month clinical trial. *Lancet Diabetes Endocrinol* 2018; **6**: 17–26.
- 208 Lacroix A, Bronstein MD, Schopohl J, et al. Long-acting pasireotide improves clinical signs and quality of life in Cushing's disease: results from a phase III study. *J Endocrinol Invest* 2020; **43**: 1613–22.
- 209 Fleseriu M, Petersenn S, Biller BMK, et al. Long-term efficacy and safety of once-monthly pasireotide in Cushing's disease: a phase III extension study. *Clin Endocrinol (Oxf)* 2019; **91**: 776–85.
- 210 Godbout A, Manavela M, Danilowicz K, Beauregard H, Bruno OD, Lacroix A. Cabergoline monotherapy in the long-term treatment of Cushing's disease. *Eur J Endocrinol* 2010; **163**: 709–16.
- 211 Petersenn S, Fleseriu M. Pituitary-directed medical therapy in Cushing's disease. *Pituitary* 2015; **18**: 238–44.
- 212 Ferriere A, Cortet C, Chanson P, et al. Cabergoline for Cushing's disease: a large retrospective multicenter study. *Eur J Endocrinol* 2017; **176**: 305–14.
- 213 Pivonello R, De Martino MC, Cappabianca P, et al. The medical treatment of Cushing's disease: effectiveness of chronic treatment with the dopamine agonist cabergoline in patients unsuccessfully treated by surgery. *J Clin Endocrinol Metab* 2009; **94**: 223–30.
- 214 Hinojosa-Amaya JM, Johnson N, Gonzalez-Torres C, et al. Depression and impulsivity self-assessment tools to identify dopamine agonist side effects in patients with pituitary adenomas. *Front Endocrinol (Lausanne)* 2020; **11**: 579606.
- 215 Fleseriu M, Biller BM, Findling JW, et al. Mifepristone, a glucocorticoid receptor antagonist, produces clinical and metabolic benefits in patients with Cushing's syndrome. *J Clin Endocrinol Metab* 2012; **97**: 2039–49.

- 216 Fleseriu M, Molitch ME, Gross C, Schteingart DE, Vaughan TB 3rd, Biller BM. A new therapeutic approach in the medical treatment of Cushing's syndrome: glucocorticoid receptor blockade with mifepristone. *Endocr Pract* 2013; **19**: 313–26.
- 217 Fleseriu M, Findling JW, Koch CA, Schlaffner SM, Buchfelder M, Gross C. Changes in plasma ACTH levels and corticotroph tumor size in patients with Cushing's disease during long-term treatment with the glucocorticoid receptor antagonist mifepristone. *J Clin Endocrinol Metab* 2014; **99**: 3718–27.
- 218 Guarda FJ, Findling J, Yuen KCJ, Fleseriu M, Nachtigall LB. Mifepristone increases thyroid hormone requirements in patients with central hypothyroidism: a multicenter study. *J Endocr Soc* 2019; **3**: 1707–14.
- 219 Daniel E, Debono M, Caunt S, et al. A prospective longitudinal study of pasireotide in Nelson's syndrome. *Pituitary* 2018; **21**: 247–55.
- 220 Ma ZY, Song ZJ, Chen JH, et al. Recurrent gain-of-function USP8 mutations in Cushing's disease. *Cell Res* 2015; **25**: 306–17.
- 221 Reincke M, Sbiera S, Hayakawa A, et al. Mutations in the deubiquitinase gene USP8 cause Cushing's disease. *Nat Genet* 2015; **47**: 31–38.
- 222 Castellnou S, Vasiljevic A, Lapras V, et al. SST5 expression and USP8 mutation in functioning and silent corticotroph pituitary tumors. *Endocr Connect* 2020; **9**: 243–53.
- 223 Hayashi K, Inoshita N, Kawaguchi K, et al. The USP8 mutational status may predict drug susceptibility in corticotroph adenomas of Cushing's disease. *Eur J Endocrinol* 2016; **174**: 213–26.
- 224 Fleseriu M, Iweha C, Salgado L, et al. Safety and efficacy of subcutaneous pasireotide in patients with Cushing's disease: results from an open-label, multicenter, single-arm, multinational, expanded-access study. *Front Endocrinol (Lausanne)* 2019; **10**: 436.
- 225 Henry RR, Ciaraldi TP, Armstrong D, Burke P, Ligueros-Saylan M, Mudaliar S. Hyperglycemia associated with pasireotide: results from a mechanistic study in healthy volunteers. *J Clin Endocrinol Metab* 2013; **98**: 3446–53.
- 226 Colao A, De Block C, Gaztambide MS, Kumar S, Seufert J, Casanueva FF. Managing hyperglycemia in patients with Cushing's disease treated with pasireotide: medical expert recommendations. *Pituitary* 2014; **17**: 180–86.
- 227 Reznik Y, Bertherat J, Borson-Chazot F, et al. Management of hyperglycaemia in Cushing's disease: experts' proposals on the use of pasireotide. *Diabetes Metab* 2013; **39**: 34–41.
- 228 Casulari LA, Naves LA, Mello PA, Pereira Neto A, Papadia C. Nelson's syndrome: complete remission with cabergoline but not with bromocriptine or cyproheptadine treatment. *Horm Res* 2004; **62**: 300–05.
- 229 Klos KJ, Bower JH, Josephs KA, Matsumoto JY, Ahlskog JE. Pathological hypersexuality predominantly linked to adjuvant dopamine agonist therapy in Parkinson's disease and multiple system atrophy. *Parkinsonism Relat Disord* 2005; **11**: 381–86.
- 230 Dodd ML, Klos KJ, Bower JH, Geda YE, Josephs KA, Ahlskog JE. Pathological gambling caused by drugs used to treat Parkinson disease. *Arch Neurol* 2005; **62**: 1377–81.
- 231 Zanettini R, Antonini A, Gatto G, Gentile R, Tesi S, Pezzoli G. Valvular heart disease and the use of dopamine agonists for Parkinson's disease. *N Engl J Med* 2007; **356**: 39–46.
- 232 Colao A, Galderisi M, Di Sarno A, et al. Increased prevalence of tricuspid regurgitation in patients with prolactinomas chronically treated with cabergoline. *J Clin Endocrinol Metab* 2008; **93**: 3777–84.
- 233 Drake WM, Stiles CE, Bevan JS, et al. A follow-up study of the prevalence of valvular heart abnormalities in hyperprolactinemic patients treated with cabergoline. *J Clin Endocrinol Metab* 2016; **101**: 4189–94.
- 234 Stiles CE, Tetteh-Wayoe ET, Bestwick J, Steeds RP, Drake WM. A meta-analysis of the prevalence of cardiac valvulopathy in hyperprolactinemic patients treated with cabergoline. *J Clin Endocrinol Metab* 2019; **104**: 523–38.
- 235 Newell-Price J, Pivonello R, Tabarin A, et al. Use of late-night salivary cortisol to monitor response to medical treatment in Cushing's disease. *Eur J Endocrinol* 2020; **182**: 207–17.
- 236 Marques JVO, Boguszewski CL. Medical therapy in severe hypercortisolism. *Best Pract Res Clin Endocrinol Metab* 2021; **35**: 101487.
- 237 Barbot M, Albiger N, Ceccato F, et al. Combination therapy for Cushing's disease: effectiveness of two schedules of treatment: should we start with cabergoline or ketoconazole? *Pituitary* 2014; **17**: 109–17.
- 238 Feelders RA, de Bruin C, Pereira AM, et al. Pasireotide alone or with cabergoline and ketoconazole in Cushing's disease. *N Engl J Med* 2010; **362**: 1846–48.
- 239 Ollivier M, Haissaguerre M, Ferriere A, Tabarin A. Should we avoid using ketoconazole in patients with severe Cushing's syndrome and increased levels of liver enzymes? *Eur J Endocrinol* 2018; **179**: L1–2.
- 240 Fontaine-Sylvestre C, Letourneau-Guillon L, Moumdjian RA, Berthelet F, Lacroix A. Corticotroph tumor progression during long-term therapy with osilodrostat in a patient with persistent Cushing's disease. *Pituitary* 2021; **24**: 207–15.
- 241 Broersen LHA, Jha M, Biermasz NR, Pereira AM, Dekkers OM. Effectiveness of medical treatment for Cushing's syndrome: a systematic review and meta-analysis. *Pituitary* 2018; **21**: 631–41.
- 242 Feelders RA, Newell-Price J, Pivonello R, Nieman LK, Hoffland LJ, Lacroix A. Advances in the medical treatment of Cushing's syndrome. *Lancet Diabetes Endocrinol* 2019; **7**: 300–12.
- 243 Valassi E, Franz H, Brue T, et al. Preoperative medical treatment in Cushing's syndrome: frequency of use and its impact on postoperative assessment: data from ERCUSYN. *Eur J Endocrinol* 2018; **178**: 399–409.
- 244 Burman P, Eden-Engstrom B, Ekman B, Karlsson FA, Schwarcz E, Wahlberg J. Limited value of cabergoline in Cushing's disease: a prospective study of a 6-week treatment in 20 patients. *Eur J Endocrinol* 2016; **174**: 17–24.
- 245 Hughes JD, Young WF, Chang AY, et al. Radiosurgical management of patients with persistent or recurrent Cushing disease after prior transsphenoidal surgery: a management algorithm based on a 25-year experience. *Neurosurgery* 2020; **86**: 557–64.
- 246 Ironside N, Chen CJ, Lee CC, Trifiletti DM, Vance ML, Sheehan JP. Outcomes of pituitary radiation for Cushing's disease. *Endocrinol Metab Clin North Am* 2018; **47**: 349–65.
- 247 Shepard MJ, Mehta GU, Xu Z, et al. Technique of whole-sellar stereotactic radiosurgery for Cushing disease: results from a multicenter, international cohort study. *World Neurosurg* 2018; **116**: e670–79.
- 248 Mehta GU, Ding D, Patibandla MR, et al. Stereotactic radiosurgery for Cushing disease: results of an international, multicenter study. *J Clin Endocrinol Metab* 2017; **102**: 4284–91.
- 249 Petit JH, Biller BM, Yock TI, et al. Proton stereotactic radiotherapy for persistent adrenocorticotropin-producing adenomas. *J Clin Endocrinol Metab* 2008; **93**: 393–99.
- 250 Gupta A, Xu Z, Kano H, et al. Upfront Gamma Knife radiosurgery for Cushing's disease and acromegaly: a multicenter, international study. *J Neurosurg* 2018; **131**: 532–38.
- 251 Castinetti F, Nagai M, Dufour H, et al. Gamma knife radiosurgery is a successful adjunctive treatment in Cushing's disease. *Eur J Endocrinol* 2007; **156**: 91–98.
- 252 Thakkar K, Lila A, Sarathi V, et al. Cabergoline may act as a radioprotective agent in Cushing's disease. *Clin Endocrinol (Oxf)* 2020; **92**: 55–62.
- 253 Starke RM, Williams BJ, Vance ML, Sheehan JP. Radiation therapy and stereotactic radiosurgery for the treatment of Cushing's disease: an evidence-based review. *Curr Opin Endocrinol Diabetes Obes* 2010; **17**: 356–64.
- 254 Sims-Williams HP, Rajapaksa K, Yianni J, et al. Long-term safety of gamma knife radiosurgery (SRS) for acromegaly. *Pituitary* 2021; **24**: 724–36.
- 255 Katznelson L. Bilateral adrenalectomy for Cushing's disease. *Pituitary* 2015; **18**: 269–73.
- 256 Guerin C, Taieb D, Treglia G, et al. Bilateral adrenalectomy in the 21st century: when to use it for hypercortisolism? *Endocr Relat Cancer* 2016; **23**: R131–42.
- 257 Ritzel K, Beuschlein F, Mickisch A, et al. Clinical review: outcome of bilateral adrenalectomy in Cushing's syndrome: a systematic review. *J Clin Endocrinol Metab* 2013; **98**: 3939–48.
- 258 Reincke M, Ritzel K, Osswald A, et al. A critical reappraisal of bilateral adrenalectomy for ACTH-dependent Cushing's syndrome. *Eur J Endocrinol* 2015; **173**: M23–32.

- 259 Osswald A, Plomer E, Dimopoulou C, et al. Favorable long-term outcomes of bilateral adrenalectomy in Cushing's disease. *Eur J Endocrinol* 2014; **171**: 209–15.
- 260 Assie G, Bahurel H, Coste J, et al. Corticotroph tumor progression after adrenalectomy in Cushing's disease: a reappraisal of Nelson's syndrome. *J Clin Endocrinol Metab* 2007; **92**: 172–79.
- 261 Fountas A, Lim ES, Drake WM, et al. Outcomes of patients with Nelson's syndrome after primary treatment: a multicenter study from 13 UK pituitary centers. *J Clin Endocrinol Metab* 2020; **105**: dgz200.
- 262 Reincke M, Albani A, Assie G, et al. Corticotroph tumor progression after bilateral adrenalectomy (Nelson's syndrome): systematic review and expert consensus recommendations. *Eur J Endocrinol* 2021; **184**: P1–16.
- 263 Jornayvaz FR, Assie G, Bienvenu-Perrard M, et al. Pregnancy does not accelerate corticotroph tumor progression in Nelson's syndrome. *J Clin Endocrinol Metab* 2011; **96**: E658–62.
- 264 Reincke M, Theodoropoulou M. Genomics in Cushing's disease: the dawn of a new era. *J Clin Endocrinol Metab* 2021; **106**: e2455–56.
- 265 Fukuoka H, Cooper O, Ben-Shlomo A, et al. EGFR as a therapeutic target for human, canine, and mouse ACTH-secreting pituitary adenomas. *J Clin Invest* 2011; **121**: 4712–21.
- 266 Neou M, Villa C, Armignacco R, et al. Pangenomic classification of pituitary neuroendocrine tumors. *Cancer Cell* 2020; **37**: 123–34.
- 267 Albani A, Perez-Rivas LG, Dimopoulou C, et al. The *USP8* mutational status may predict long-term remission in patients with Cushing's disease. *Clin Endocrinol (Oxf)* 2018; **89**: 454–58.
- 268 Tatsi C, Flippo C, Stratakis CA. Cushing syndrome: old and new genes. *Best Pract Res Clin Endocrinol Metab* 2020; **34**: 101418.
- 269 Carroll PV, Monson JP, Grossman AB, et al. Successful treatment of childhood-onset Cushing's disease is associated with persistent reduction in growth hormone secretion. *Clin Endocrinol (Oxf)* 2004; **60**: 169–74.
- 270 Ferrigno R, Hasenmajer V, Caiulo S, et al. Paediatric Cushing's disease: epidemiology, pathogenesis, clinical management and outcome. *Rev Endocr Metab Disord* 2021; published online Jan 30. <https://doi.org/10.1007/s11154-021-09626-4>.
- 271 Lodish MB, Keil MF, Stratakis CA. Cushing's syndrome in pediatrics: an update. *Endocrinol Metab Clin North Am* 2018; **47**: 451–62.
- 272 Tatsi C, Neely M, Flippo C, Bompou ME, Keil M, Stratakis CA. Recovery of hypothalamic-pituitary-adrenal axis in paediatric Cushing disease. *Clin Endocrinol (Oxf)* 2021; **94**: 40–47.
- 273 Davies JH, Storr HL, Davies K, et al. Final adult height and body mass index after cure of paediatric Cushing's disease. *Clin Endocrinol (Oxf)* 2005; **62**: 466–72.
- 274 Makri A, Akshintala S, Derse-Anthony C, et al. Multiple endocrine neoplasia type 2B presents early in childhood but often is undiagnosed for years. *J Pediatr* 2018; **203**: 447–49.
- 275 Makri A, Bonella MB, Keil MF, et al. Children with *MEN1* gene mutations may present first (and at a young age) with Cushing disease. *Clin Endocrinol (Oxf)* 2018; **89**: 437–43.

Copyright © 2021 Elsevier Ltd. All rights reserved.