

## REVIEW ARTICLE

## DRUG THERAPY

## Asthma

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ACCORDING TO SURVEY DATA FOR WHICH THE DIAGNOSIS OF ASTHMA WAS based on a physician's assessment, it is estimated that approximately 7% of Americans have current asthma.<sup>1,2</sup> The disease affects people of all races and ethnic groups worldwide, from infancy to old age, with slightly more boys than girls affected and, after puberty, more women than men. Dramatic increases in the prevalence of atopy and asthma have occurred over the past few decades in Westernized countries<sup>3</sup> and more recently in less-developed nations.<sup>4</sup> Estimates suggest that as many as 300 million persons are affected worldwide.<sup>5</sup>

In the 1970s and 1980s, severe asthmatic exacerbations (as indicated by emergency department visits and hospitalizations for asthma) and asthma-related mortality rose steeply in the United States. Yet despite the persistently high prevalence of disease, the most recently available data indicate improved outcomes, with fewer annual hospitalizations for asthmatic attacks and fewer asthma-related deaths.<sup>6</sup> Among the possible explanations for these favorable trends are the more widespread preventive use of inhaled corticosteroids and the introduction over the past 10 to 15 years of new, highly effective medications and improved medication formulations for the treatment of asthma.

Airway obstruction in asthma and the consequent symptoms of cough, shortness of breath, chest tightness, and wheezing are caused by some combination of airway smooth-muscle constriction and inflammation of the bronchi. The former can be severe, leading to life-threatening narrowing and closure of airways, even in the absence of mucous plugging. Both abnormal smooth-muscle contractility<sup>7</sup> and excess smooth-muscle mass<sup>8</sup> may contribute. Airway inflammation in asthma consists of mucosal, submucosal, and adventitial edema; cellular infiltration, particularly by eosinophils (and in some cases, neutrophils) and activated helper T lymphocytes<sup>9</sup> as well as mast cells that (unlike mast cells in other eosinophilic airway diseases) infiltrate smooth-muscle bundles<sup>10</sup>; increased airway secretions, including secreted mucus, desquamated lining cells, and intraluminal eosinophils; capillary engorgement; hyperplasia of smooth muscle; and deposition of excess collagen, particularly immediately beneath the basement membrane of the epithelium.<sup>11,12</sup>

Traditionally, drugs used to treat asthma were categorized according to their predominant effect — relaxation of airway smooth muscle (bronchodilators) or suppression of airway inflammation (antiinflammatory drugs). Newer medications (e.g., the leukotriene modifiers) and drug combinations (e.g., inhaled corticosteroids combined with long-acting  $\beta$ -adrenergic agonists) have dual effects, resisting such traditional dichotomization. Now, asthma medications are classified according to their roles in the overall management of asthma (quick relief or long-term control), a model that is particularly useful when speaking to patients about their asthma medicines.

All patients with asthma should have available a quick-relief bronchodilator for use as needed. Consensus opinion suggests that when quick-acting bronchodilators are

needed for symptom relief more than 2 days per week (or more than twice a month for nighttime awakenings caused by asthmatic symptoms), controller medications should be prescribed.<sup>2,13</sup>

### QUICK RELIEF

Quick-acting  $\beta$ -adrenergic agonists administered by inhalation are the most effective therapy for rapid reversal of airflow obstruction and prompt relief of asthmatic symptoms. Most widely used are the short-acting,  $\beta_2$ -selective, adrenergic agonists: albuterol (commonly known as salbutamol outside the United States), levalbuterol, and pirbuterol (Table 1). Metaproterenol delivered by metered-dose inhaler has recently been withdrawn from the market.

The short-acting  $\beta$ -agonists all have an onset of action in 5 minutes or less, with a peak effect in 30 to 60 minutes and a duration of action of 4 to 6 hours.<sup>14</sup> With regular use of a bronchodilator (four or more times daily), the potency (as measured by the increase in maximal expiratory flow) does not decline, but the duration of action is slightly shortened.<sup>15,16</sup> Because a regular schedule of administration four times a day does not improve outcomes, as compared with as-needed administration<sup>17</sup> (and, in patients with certain genotypic variants of the  $\beta$ -receptor, may have a deleterious effect),<sup>18,19</sup> the short-acting  $\beta$ -agonists are recommended for use only as needed for relief of symptoms (or before anticipated exposure to known asthmatic triggers, especially exercise). The practice of administering a short-acting  $\beta$ -agonist before using an inhaled corticosteroid to improve delivery of the corticosteroid to the lower airways has been abandoned as unnecessary.<sup>20</sup> Similarly, there is no need for patients to wait more than 10 to 15 seconds between puffs when a dose of two or more puffs is recommended.<sup>21</sup>

In patients with moderate or severe airflow obstruction, a log-linear dose–response curve for bronchodilation can be demonstrated for short-acting  $\beta$ -agonists administered at very high doses (up to 4000  $\mu$ g of albuterol by metered-dose inhaler).<sup>15</sup> Dose-dependent, sympathomimetic-type side effects, including tremor, anxiety, heart pounding, and tachycardia (but not hypertension), are common, and a small dose-dependent decrease in serum potassium and magnesium levels is detectable. However, at the usual dose (two puffs per administration), unpleasant stimulatory side ef-

fects are uncommon. Although their effectiveness may be diminished somewhat, inhaled  $\beta$ -agonist bronchodilators are not contraindicated in patients who are simultaneously taking beta-blockers.<sup>22,23</sup>

The decision about which of the various short-acting  $\beta$ -agonists to use is based largely on cost and the patient's or physician's preference. Pirbuterol is the only one available in a breath-actuated metered-dose inhaler, a device meant to optimize medication delivery by releasing a spray of medication only on the patient's initiation of inspiration. Levalbuterol, the purified D-rotatory isomer of albuterol, was developed for the purpose of eliminating side effects, which some argue are limited to the S-rotatory isomer.<sup>24</sup> However, when delivered by metered-dose inhaler, levalbuterol has an efficacy and side-effect profile that is indistinguishable from that of the racemic mixture of molecules in albuterol.<sup>25</sup> Albuterol has been made available in a metered-dose inhaler free of chlorofluorocarbons (CFCs), and CFC-containing albuterol inhalers were taken off the market on December 31, 2008.<sup>26</sup> Like CFCs, the alternative propellant, hydrofluoroalkane (HFA), is inert in the human airway, but unlike CFCs, it does not contribute to depletion of the stratospheric ozone layer. For more information on HFA-containing metered-dose inhalers, see the Supplementary Appendix, available with the full text of this article at NEJM.org. A Supplementary Video, also available at NEJM.org in an article by Hendeles et al.,<sup>26</sup> demonstrates the use of an HFA albuterol inhaler. The HFA inhalers are equipotent to the CFC-propelled inhalers,<sup>27</sup> can be used with valved holding chambers (spacers) in patients with poor inhalational technique,<sup>28</sup> and provide bronchodilation comparable to nebulized albuterol when a sufficient number of puffs is administered and inhalational technique is good.<sup>29</sup>

Short-acting  $\beta$ -agonists that are to be swallowed, in either tablet or liquid form, should be discouraged, despite their seeming convenience (especially for very young children). They take longer to start working, are less potent, and are associated with more frequent side effects than inhaled short-acting  $\beta$ -agonists.<sup>30</sup> Similarly, anticholinergic bronchodilators such as ipratropium are not recommended (or approved by the Food and Drug Administration [FDA]) for quick relief of asthmatic symptoms. They take longer to start working (20 to 30 minutes) and cause less bron-

Table 1. Short-Acting  $\beta$ -Adrenergic Agonists.\*

| Drug           | Brand Name   | Formulation              | Dose                                | No. of Doses per MDI Canister | Rating in Pregnancy† | Comments   |
|----------------|--|--------------------------|-------------------------------------|-------------------------------|----------------------|--|
| Albuterol      | Ventolin (GlaxoSmithKline), ProAir (Teva), Proventil (Schering-Plough) | MDI-HFA                  | 90 $\mu$ g/puff                     | 200                           | C                    | CFC-driven albuterol MDIs were taken off the market on December 31, 2008; generic albuterol HFA inhalers are not yet available |
|                | AccuNeb (Dey), generic   | Liquid for nebulization  | 0.63, 1.25, or 2.5 mg/vial; 5 mg/ml |                               | C                    |  |
|                | Proventil Repetabs, Vospire ER (DAVA Pharmaceuticals)                  | Extended-release tablets | 4 or 8 mg                           |                               | C                    |  |
|                | Proventil, generic   | Tablets                  | 2 or 4 mg                           |                               | C                    |  |
|                | Generic  | Syrup                    | 2 mg/5 ml                           |                               | C                    |  |
| Levalbuterol   | Xopenex (Sepracor)   | MDI-HFA                  | 45 $\mu$ g/puff                     | 200                           | C                    | Single stereoisomer derived from albuterol   |
|                |  | Liquid for nebulization  | 0.31, 0.63, or 1.25 mg/vial         |                               | C                    |  |
| Metaproterenol | Alupent (Boehringer Ingelheim), generic                                | Liquid for nebulization  | 10 or 15 mg/vial; 50 mg/ml          |                               | C                    | Less $\beta_2$ selectivity than albuterol; manufacture of metaproterenol MDI was discontinued in July 2008                     |
|                | Alupent, generic   | Tablets or syrup         | 10 or 20 mg; 10 mg/5 ml             |                               | C                    |  |
| Pirbuterol     | Maxair (Graceway)  | MDI-CFC                  | 200 $\mu$ g/puff                    | 400                           | C                    | Breath-actuated MDI  |

\* CFC denotes chlorofluorocarbons, HFA hydrofluoroalkane, and MDI metered-dose inhaler.

† A pregnancy rating of C indicates that a risk to the fetus cannot be ruled out.

chodilation than inhaled  $\beta$ -agonist bronchodilators.<sup>31</sup> Anticholinergic bronchodilators should be used only in the rare case of a patient with intolerance to all  $\beta$ -agonist bronchodilators or for the treatment of severe asthmatic attacks<sup>32</sup> or asthmatic attacks induced by beta-blockers.<sup>2</sup>

A novel approach to asthma management, not yet adopted in the United States, combines a short-acting  $\beta$ -agonist with an inhaled corticosteroid in a single device, administered as needed for symptom relief. Use of the device has been associated with favorable outcomes in patients with mild asthma, as compared with the use of albuterol alone as needed.<sup>33</sup> Similarly, the long-acting  $\beta$ -agonist bronchodilator with a quick onset of action (formoterol) is being used in combination with an inhaled corticosteroid in a single inhaler for both maintenance and rescue therapy.<sup>34,35</sup> The safety of this approach in a broad and diverse patient population remains to be ascertained.

#### LONG-TERM CONTROL

Achieving good long-term control of asthma (infrequent asthmatic symptoms, an unrestricted level of activity, normal or near-normal lung function, and rare asthmatic attacks requiring emergency care) requires a multifaceted approach: avoidance of environmental stimuli that can provoke bronchoconstriction and acute and chronic airway inflammation; monitoring of changes in disease activity; in some cases, allergen immunotherapy; and drug therapy. The use of controller medications should be intensified (or stepped up) until good asthma control is achieved, including a reduction of the number of asthmatic attacks requiring systemic corticosteroids to no more than one yearly. Inhaled corticosteroids constitute the drug class that has had the greatest effect in helping patients achieve well-controlled asthma.

#### INHALED CORTICOSTEROIDS

Corticosteroids have proved effective in the treatment of asthma, as they have in many other inflammatory diseases, because of their multiplicity of antiinflammatory activities, including a broad effect on the transcription (both up-regulation and down-regulation) of many genes.<sup>36,37</sup> In airway-biopsy specimens from patients with asthma who have had prolonged treatment with inhaled corticosteroids, the histologic abnormalities that are typical of asthma have been shown to diminish.

Changes include fewer mast cells, eosinophils, T lymphocytes, and dendritic cells in the mucosa and submucosa<sup>38</sup>; reduced goblet-cell hyperplasia and epithelial-cell injury<sup>39</sup>; and decreased vascularity.<sup>40</sup>

Along with suppression of airway inflammation, nonspecific bronchial hyperresponsiveness typically decreases by a factor of two to four.<sup>41</sup> Beneficial clinical outcomes include fewer asthmatic symptoms, increased lung function, improved asthma-specific quality of life, and fewer asthmatic exacerbations, including severe attacks resulting in hospitalization<sup>42</sup> or death.<sup>43</sup> Optimistic predictions to the contrary, evidence is for the most part lacking to indicate that long-term use of inhaled corticosteroids can prevent the progressive decline in lung function observed in some persons with asthma.<sup>44,45</sup> Inhaled steroids suppress but do not cure asthmatic inflammation: in a stable phase of the disease, markers of airway inflammation (e.g., exhaled nitric oxide concentrations and sputum eosinophilia) and bronchial hyperresponsiveness return to baseline approximately 2 weeks after the use of inhaled corticosteroids has been stopped.<sup>46,47</sup>

Not all patients benefit equally from inhaled corticosteroids. For instance, current cigarette smokers are less likely to derive the same antiasthmatic effects as nonsmokers.<sup>48</sup> Neutrophilic inflammation of the airways is less likely to respond to treatment than is eosinophilic inflammation. Genetic differences in persons with asthma may also be predictive of nonresponsiveness to corticosteroids.<sup>49</sup>

Most of the currently available inhaled corticosteroids, when swallowed and systemically absorbed from the gastrointestinal tract, undergo extensive first-pass metabolic inactivation in the liver before reaching the systemic circulation.<sup>50</sup> In addition, because in general less than 20% of the delivered dose is deposited onto the airways, only small amounts are available for systemic absorption across the respiratory tract mucosa. With the use of changes in hypothalamic-pituitary-adrenal function as an assay, a systemic effect can be seen with inhaled-corticosteroid administration at doses as low as 88  $\mu\text{g}$  of fluticasone per day.<sup>51</sup> However, virtually no clinically important, long-term adverse systemic effects are observed among adults taking low-to-medium doses. At high doses (usually  $>1000$   $\mu\text{g}$  of beclomethasone per day or the equivalent), the risks of skin bruising

**Table 2. Inhaled Corticosteroids.\***

| Drug                        | Brand Name                    | Formulation†‡                      | Dose per Inhalation<br>µg   | No. of Doses<br>per Canister   | Rating in<br>Pregnancy‡ | Patient Age<br>yr                         | Comments   |
|-----------------------------|-------------------------------|------------------------------------|---|--|-------------------------|---|--|
| Beclomethasone              | Qvar (Teva)                   | MDI-HFA                            | 40 or 80  | 100  | C                       | ≥5  | Prepared as an aerosol solution (rather than suspension), with smaller particle size         |
| Budesonide                  | Pulmicort (AstraZeneca)       | DPI or suspension for nebulization | DPI: 90 or 180; suspension for nebulization: 250 or 500   | DPI: 60 or 120; suspension for nebulization: prefilled single-dose vials | B                       | DPI: ≥6; suspension for nebulization: 1-8 | Built-in dose counter  |
| Ciclesonide                 | Alvesco (Sepracor)            | MDI-HFA                            | 80 or 160   | 60   | C                       | ≥12                                       | Prepared as an aerosol solution, activated by airway esterases, approved for twice-daily use |
| Flunisolide                 | Aerobid (Forest Laboratories) | MDI-CFC                            | 250   | 100  | C                       | ≥6  | Available with menthol flavoring as Aerobid-M  |
| Fluticasone                 | Flovent (GlaxoSmithKline)     | MDI-HFA or DPI                     | MDI-HFA: 44, 110, or 220; DPI: 50 or 100  | MDI-HFA: 120; DPI: 60  | C                       | ≥4  | Built-in dose counter with both MDI and DPI  |
| Mometasone                  | Asmanex (Schering-Plough)     | DPI                                | 110 or 220  | 30; 30; 60; 120  | C                       | ≥4  | Approved for once-daily use; built-in dose counter   |
| Triamcinolone               | Azmacort (Abbott)             | MDI-CFC                            | 75  | 240  | C                       | ≥6  | Built-in small-volume spacer   |
| In combination with LABA    |                               |                                    |   |  |                         |   |  |
| Budesonide with formoterol  | Symbicort (AstraZeneca)       | MDI-HFA                            | 80 or 160 (with 4.5 µg of formoterol)   | 120  | C                       | ≥12                                       | 2 Puffs twice daily; built-in dose counter   |
| Fluticasone with salmeterol | Advair (GlaxoSmithKline)      | MDI-HFA or DPI                     | MDI-HFA: 45, 115, or 230 (with 21 µg of salmeterol); DPI: 100, 250, or 500 (with 50 µg of salmeterol) | MDI-HFA: 120; DPI: 60  | C                       | MDI-HFA: ≥12; DPI: ≥4                     | MDI-HFA: 2 puffs twice daily; DPI: 1 inhalation twice daily; built-in dose counter           |

\* Fluticasone and mometasone are more potent, microgram for microgram, by a factor of approximately 2:1 than beclomethasone, budesonide, and flunisolide. The most recently released inhaled corticosteroid, ciclesonide, is an ester prodrug — inactive until hydrolyzed to desisobutyl-ciclesonide by esterases endogenous to airway epithelium. Preliminary data suggest that ciclesonide is associated with a lower incidence of oral candidiasis than fluticasone<sup>58</sup> and is not associated with growth retardation in children when given in conventional doses.<sup>59</sup> Mometasone has been approved for once-daily use, although it is likely that other inhaled corticosteroids can also be administered once daily for patients with mild, well-controlled asthma.<sup>60,61</sup> CFC denotes chlorofluorocarbons, DPI dry-powder inhaler, HFA hydrofluoroalkane, LABA long-acting β-agonist, and MDI metered-dose inhaler.

† A pregnancy rating of B indicates that there is no evidence of fetal risk in humans, and a rating of C that a risk to the fetus cannot be ruled out.

‡ Other formulations are available outside the United States.

ing, cataracts,<sup>52</sup> elevated intraocular pressure,<sup>53</sup> and accelerated loss of bone mass<sup>54</sup> increase. In children, growth retardation is a concern. Expected growth decreases by an average of approximately 1 cm in the first year after instituting inhaled corticosteroids in growing children,<sup>45,55</sup> but evidence from studies in prepubescent school-age children suggests that even when these children continue to receive long-term treatment with inhaled corticosteroids, they ultimately reach their normal predicted height.<sup>45,56</sup>

Pharyngeal and laryngeal side effects of inhaled corticosteroids include sore throat, coughing on inhalation of the medication, weak or hoarse voice, and candidiasis. Rinsing the mouth after each administration of the medication and using a valved holding chamber when it is delivered with a metered-dose inhaler are two techniques that can minimize the risk of oral candidiasis (thrush). (Use of the valved holding chamber also reduces the amount of medication available for systemic absorption from the oropharynx.) Cough can usually be overcome by changing either the inhaled corticosteroid medication or the delivery system. Dysphonia, generally intermittent, is thought to be due to laryngeal edema and mucosal thickening or possibly myopathy.<sup>57</sup> It usually resolves with temporary cessation of the medication and may also do so with a change in aerosol generation and flow pattern (e.g., switching from a dry-powder inhaler to a metered-dose inhaler with valved holding chamber.)

When first introduced for the treatment of asthma in the mid-1970s, the inhaled corticosteroid beclomethasone was prescribed for use four times daily, and each puff of medication from a metered-dose inhaler sold in the United States

contained only 42  $\mu\text{g}$  of medication. Since then, additional corticosteroid preparations have become available, including drugs that are more potent, deliver a larger dose per inhalation, and are recommended for use once or twice daily, features that have contributed to improved efficacy and compliance (Table 2).

There are differences among the various inhaled corticosteroids.<sup>62,63</sup> For the most part, choices are based on the convenience of the dosing schedule (once or twice daily) and method of delivery (metered-dose inhaler, dry-powder inhaler, or suspension for nebulization), the starting dose and flexibility in making dose adjustments, the cost to the patient, and observed side effects. Only minor differences in the products' therapeutic outcomes have been found.

The use of high-dose inhaled corticosteroids has proved effective for the control of severe persistent asthma.<sup>64</sup> However, the dose–therapeutic-response (improvement in expiratory flow) curve for inhaled corticosteroids is relatively flat, whereas the dose–systemic-absorption curve appears to be linear.<sup>51</sup> As a result, strategies that can achieve asthma control without using high doses of inhaled corticosteroids are desirable, and reduction of the inhaled-corticosteroid dose in patients with well-controlled asthma (referred to as “stepping down” treatment) can often be achieved without diminishing asthma control.<sup>65</sup>

#### INHALED LONG-ACTING $\beta$ -AGONIST BRONCHODILATORS

The inhaled long-acting  $\beta$ -agonists, salmeterol and formoterol (Tables 2 and 3), have largely replaced the older long-acting bronchodilators — orally administered, slow-release albuterol and theophylline. Long-acting  $\beta$ -agonists are potent broncho-

**Table 3. Inhaled Long-Acting  $\beta$ -Agonist Bronchodilators.\***

| Drug         | Brand Name                 | Formulation               | Dose<br>$\mu\text{g}$ | Patient Age<br>yr | Rating in<br>Pregnancy† | Comments                         |
|--------------|----------------------------|---------------------------|-----------------------|-------------------|-------------------------|----------------------------------|
| Arformoterol | Brovana (Sepracor)         | Liquid for aerosolization | 15/vial               | Adults            | C                       | Approved for COPD but not asthma |
| Formoterol   | Foradil (Schering-Plough)  | Single-dose DPI           | 12/capsule            | $\geq 5$          | C                       | Rapid onset of action            |
|              | Perforomist (Dey)          | Liquid for aerosolization | 20/vial               | Adults            | C                       | Approved for COPD but not asthma |
| Salmeterol   | Serevent (GlaxoSmithKline) | DPI (60 doses per device) | 50/inhalation         | $\geq 4$          | C                       | Multidose DPI                    |

\* COPD denotes chronic obstructive pulmonary disease, and DPI dry-powder inhaler.

† A pregnancy rating of C indicates that a risk to the fetus cannot be ruled out.

dilators (with a bronchodilator effect similar to that of the short-acting  $\beta$ -agonists), have sustained activity for more than 12 hours, and because of their high degree of adrenergic  $\beta$ -2 specificity, have few side effects (generally mild sympathomimetic-type stimulation, including occasional muscle cramps and tachycardia).<sup>66</sup> They have none of the food–drug and drug–drug interactions that complicate the use of theophylline, and toxicity from drug overdosing is exceedingly rare, in contrast to the effects of theophylline overdosing.

As with short-acting  $\beta$ -agonists, regular use of long-acting  $\beta$ -agonists results in only mild tachyphylaxis to the maximal bronchodilator effect and the duration of action of these drugs.<sup>66</sup> In contrast, the bronchoprotective effect of long-acting  $\beta$ -agonists (i.e., their inhibition of exercise-induced bronchoconstriction) rapidly wanes with regular use,<sup>67,68</sup> a contrary pharmacologic effect that has not been fully explained. With rare exceptions,<sup>69</sup> the quick symptom relief provided by short-acting  $\beta$ -agonists is not impeded by regular use of long-acting  $\beta$ -agonists.<sup>70</sup> Variation in the structure of the  $\beta$ -adrenergic receptor, as determined by genetic polymorphisms that are common in the U.S. population (15 to 20%), may limit the effectiveness of long-acting  $\beta$ -agonists in some patients.<sup>71</sup>

The fact that long-acting  $\beta$ -agonists can provide sustained improvement in lung function may tempt clinicians to use them as a long-term controller medication without concomitant use of an antiinflammatory inhaled corticosteroid. However, this strategy results in unsuppressed airway inflammation and an unacceptably high rate of asthmatic exacerbations.<sup>47</sup> Long-acting  $\beta$ -agonists should not be used without concomitant antiinflammatory therapy in the treatment of asthma.

As therapy added to or combined with inhaled corticosteroids, long-acting  $\beta$ -agonists have proved effective in reducing daytime and especially nighttime symptoms, improving lung function, reducing the risk of exacerbations, and minimizing the required dose of inhaled corticosteroids.<sup>72</sup> Comparisons of the use of inhaled corticosteroids in combination with long-acting  $\beta$ -agonists and the use of higher doses of inhaled corticosteroids alone show that the combination therapy is associated with more favorable outcomes (while maintaining lower exposure to corticosteroids).<sup>73,74</sup> Pharmacologic evidence provides theoretical support for a favorable interaction between these

two classes of medications: in vitro studies show that corticosteroids improve  $\beta$ -receptor–mediated signaling in the lung, and  $\beta$ -agonists enhance the transcription of genes under the influence of corticosteroids.<sup>75</sup> Combination therapy (a long-acting  $\beta$ -agonist combined with an inhaled corticosteroid in a single inhaler) (Table 2) ensures concomitant use of an antiinflammatory drug and optimizes compliance because of greater convenience. Its major disadvantage is that adjusting the dose of inhaled corticosteroids without changing the dose of  $\beta$ -agonist (e.g., increasing the corticosteroid dose during an asthmatic exacerbation) requires changing devices or adding a separate inhaled corticosteroid inhaler.

The life-changing benefit that many patients with moderate or severe persistent asthma have experienced with the use of a long-acting  $\beta$ -agonist together with an inhaled corticosteroid must be counterbalanced against the results of the Salmeterol Multicenter Asthma Research Trial (SMART),<sup>76</sup> in which the addition of a long-acting  $\beta$ -agonist to “usual therapy” was associated with an increased risk of fatal and near-fatal asthmatic attacks, as compared with “usual therapy” alone. It has been pointed out that a minority of subjects in SMART were taking inhaled corticosteroids and that no increased asthma-related mortality has ever been reported among patients taking both a long-acting  $\beta$ -agonist and an inhaled corticosteroid.<sup>77,78</sup> Nonetheless, the mechanism by which salmeterol caused a greater number of asthma-related deaths, among both black and white subjects, remains uncertain, and a black-box warning is therefore included in the prescription-labeling information (or package insert) for all products containing either salmeterol or formoterol. In addition, national and international expert panels<sup>2,13</sup> have recommended the use of long-acting  $\beta$ -agonists only for patients in whom inhaled corticosteroids alone either have failed to achieve good asthma control or, for initial therapy, would not be expected to bring about good control. Future guidelines on the treatment of asthma will need to wrestle with appropriate application of the recent observation that once-daily administration of a long-acting  $\beta$ -agonist in combination with an inhaled corticosteroid provides good control in patients with mild persistent asthma.<sup>79</sup>

Features distinguishing the two long-acting  $\beta$ -agonists are both practical and theoretical.<sup>80</sup>

The onset of action of formoterol occurs within 5 minutes, a period similar to that for short-acting  $\beta$ -agonists, whereas salmeterol has a slower onset of action (15 to 20 minutes). For this reason, in some countries other than the United States, a combination formoterol–inhaled-corticosteroid inhaler is recommended both for quick relief of asthmatic symptoms and, when used regularly, for long-term control.<sup>34</sup> Formoterol is a full agonist in its action at the  $\beta$ -receptor, whereas salmeterol is a partial agonist (and partial antagonist). The implication of this pharmacologic distinction, particularly as it might apply to the risk of fatal asthmatic attacks, is uncertain.

**LEUKOTRIENE MODIFIERS**

The cysteinyl leukotriene-receptor antagonists, montelukast, zafirlukast, and pranlukast (the last not available in the United States) (Table 4), block the action of leukotriene C<sub>4</sub>, D<sub>4</sub>, and E<sub>4</sub> at the type 1 cysteinyl leukotriene receptor.<sup>81</sup> Bronchodilation occurs within hours of the first dose and is maximal within the first few days after administration.<sup>82,83</sup> Levels of circulating blood eosinophils decrease in response to treatment with leukotriene-receptor antagonists.<sup>82,83</sup> However, when indirect measures of airway inflammation (e.g., sputum eosinophilia and levels of exhaled nitric oxide) are used to determine the outcome, the effect of leukotriene-receptor antagonists on airway inflammation, as compared with that of placebo, has been variable.<sup>84-86</sup>

Leukotriene-receptor antagonists can be administered as tablets once (in the case of montelukast) or twice (in the case of zafirlukast) daily.

Montelukast is available in chewable tablets and oral granules (to be mixed with food) for young children. The recommendation to administer montelukast once daily in the evening was based on the timing of its use in the seminal trials submitted to the FDA at the time of application for approval. No data indicate a greater benefit with administration in the evening as compared with dosing at any other time of day.<sup>87</sup>

Zileuton inhibits production of the cysteinyl leukotrienes (and of leukotriene B<sub>4</sub>, a potent chemoattractant for neutrophils) by antagonizing the action of 5-lipoxygenase. An extended-release formulation is now available, making twice-daily dosing possible. No clinical trial has directly compared the efficacy of zileuton with that of a leukotriene-receptor antagonist or has tested the effects of their use in combination. Some clinicians have found zileuton to be more beneficial than leukotriene-receptor antagonists in triad asthma (asthma, aspirin sensitivity, and nasal polyposis), in terms of both controlling asthma and shrinking nasal polyps.<sup>88</sup>

Zileuton causes a reversible chemical hepatitis in 2 to 4% of patients. Hepatic function should be monitored monthly for the first 3 months of therapy, about every 3 months for the remainder of the first year, and periodically thereafter. Reports of the emergence of the Churg–Strauss syndrome (an eosinophilic vasculitis with granulomatosis complicating the course of asthma) in patients recently started on a leukotriene-receptor antagonist (often with concomitant tapering of oral corticosteroids)<sup>89,90</sup> may reflect unmasking of pre-existing cases of Churg–Strauss vasculitis,<sup>91,92</sup>

**Table 4. Leukotriene Modifiers.**

| Drug        | Brand Name                          | Formulation                               | Dose<br>mg   | Patient Age<br>yr  | Rating in<br>Pregnancy* | Comments                                 |
|-------------|-------------------------------------|---|--|--|-------------------------|--|
| Montelukast | Singulair<br>(Merck)                | Granules, chewable<br>tablets, or tablets | Granules: 4; chewable<br>tablets: 4 or 5;<br>tablets: 10 | Granules: 1–2; chewable<br>tablets: 2–5 for the<br>4-mg dose, 6–14 for<br>the 5-mg dose; tab-<br>lets: $\geq 15$ | B                       | Once-daily use                           |
| Zafirlukast | Accolate<br>(AstraZeneca)           | Tablets                                   | 10 or 20   | 5–11 for the 10-mg<br>dose, $\geq 12$ for the<br>20-mg dose  | B                       | One tablet twice daily                   |
| Zileuton    | Zyflo (Cornerstone<br>Therapeutics) | Extended-release<br>tablets               | 600  | $\geq 12$  | C                       | Two tablets twice daily<br>(after meals) |

\* A pregnancy rating of B indicates that there is no evidence of fetal risk in humans, and a rating of C that a risk to the fetus cannot be ruled out.



although the possibility of a causal association remains debated.<sup>93</sup> In general, the leukotriene-receptor antagonists have been considered virtually free of side effects, and one (montelukast) has been approved for the treatment of asthma in children as young as 1 year old. Recent postmarketing reports have described a few cases in which depression and suicidal ideation developed in children taking montelukast. No cause-and-effect relationship has been established, and on review of all available placebo-controlled clinical trials data, the FDA found no increased risk of suicidal ideation or suicide for any of the leukotriene modifiers. The possibility of medication-induced mood and behavioral changes remains under review.<sup>94</sup>

Because of their perceived safety and convenience, leukotriene-receptor antagonists have largely replaced the cromoglycates (cromolyn and nedocromil) as the noncorticosteroid treatment of choice, especially for young children, in whom medication delivery by aerosol is often a struggle. Cromolyn requires administration four times daily by metered-dose inhaler or nebulizer, provides limited long-term asthma control, and unlike leukotriene-receptor antagonists, has never been shown to have an additive benefit when used in combination with inhaled corticosteroids.

Short-term, double-blind, placebo-controlled trials have shown improved lung function, better scores on asthma-related quality-of-life questionnaires, and fewer asthmatic attacks among patients treated with leukotriene modifiers.<sup>82,83,95,96</sup> Persons with asthma who are obese,<sup>97</sup> who smoke cigarettes,<sup>48</sup> or who have associated aspirin sensitivity<sup>88,98,99</sup> may particularly benefit from treatment with leukotriene modifiers. In the future, identification of specific interindividual variations in the genes coding for enzymes along the leukotriene metabolic pathway may prove clinically useful in predicting whether a patient will have a response to treatment.<sup>100</sup> Currently, a therapeutic trial is often used; symptomatic and objective improvement, if they are to occur, are generally observed within the first month of therapy.

Overall, inhaled corticosteroids provide better asthma control than leukotriene modifiers.<sup>86,96,101-103</sup> As a result, an inhaled corticosteroid is the recommended drug of first choice in the treatment of patients with persistent asthma, including children of all ages.<sup>2</sup> Leukotriene-receptor antagonists are an alternative treatment for mild persistent asthma. For patients of any age

in whom good asthma control is not achieved with the use of a leukotriene modifier, transition to an inhaled corticosteroid is indicated. For patients with more severe asthma, the addition of a leukotriene-receptor antagonist to a low dose of an inhaled corticosteroid may improve asthma control,<sup>104,105</sup> but other treatment combinations (specifically, an inhaled corticosteroid plus long-acting  $\beta$ -agonist) are more effective.<sup>106,107</sup>

#### ANTI-IgE THERAPY

The anti-IgE monoclonal antibody, omalizumab, is the first biologic immunoregulatory agent available to treat asthma. It binds to the portion of IgE that recognizes its high-affinity receptor (Fc $\epsilon$ R1) on the surface of mast cells and basophils. When given intravenously, omalizumab reduces circulating IgE levels by 95% and can result in levels of free IgE of 10 IU per milliliter or less, a target thought to be clinically relevant for inhibiting allergic reactions in the airways.<sup>108</sup> Its use also results in down-regulation of expression of Fc $\epsilon$ R1 on the surface of mast and other immune-modulating cells (basophils, monocytes, and dendritic cells).<sup>109</sup> In contradistinction to allergen immunotherapy, treatment with omalizumab is not restricted in its effects to any specific allergen or group of allergens.

Omalizumab is administered subcutaneously every 2 or 4 weeks, depending on the dose. The dose is based on the patient's weight and blood IgE level. Reactions at the injection site (e.g., hives) are uncommon, and systemic allergic reactions (i.e., anaphylaxis) occur in 1 to 2 patients per 1000. Most but not all systemic reactions occur within 2 hours after administration of the first few doses. Patients are asked to remain under medical observation for 2 hours after each of their first three injections and for 30 minutes after each subsequent injection and to carry with them for the next 24 hours prefilled epinephrine-containing auto-injectors for self-administration, if needed.<sup>110</sup>

Omalizumab is indicated for the treatment of moderate and severe persistent asthma when inhaled corticosteroids, long-acting  $\beta$ -agonists, and leukotriene modifiers have not provided adequate control or cannot be used because of intolerable adverse effects. The currently approved dosing range for omalizumab limits administration to patients with blood IgE levels between 30 and 700 IU per milliliter; documented sensitization to a perennial aeroallergen (e.g., dust mites, ani-

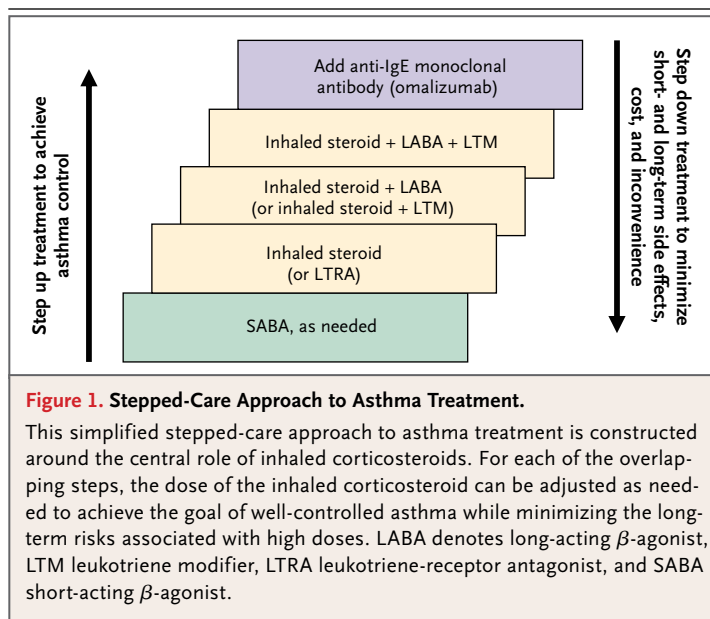
mal dander, mold, or cockroaches) is an additional criterion for patient selection.

Omalizumab has been approved for use in adults and children 12 years of age or older. For patients in this age range, the drug has not been shown to be “disease modifying” in the sense that it is not known to prevent long-term changes in lung function or to result in a disease remission (as indicated by drug discontinuation without recurrence of asthmatic symptoms). Treatment with omalizumab has been found to reduce the frequency of asthmatic exacerbations, even among patients already taking many other controller medications.<sup>111</sup> In patients treated with an inhaled corticosteroid alone, the addition of omalizumab, as compared with placebo, permitted a greater reduction of the inhaled-corticosteroid dose, with preserved or slightly improved lung function and with slightly less need for a rescue bronchodilator.<sup>112,113</sup>

One of the greatest drawbacks to the more widespread use of omalizumab is cost, roughly \$10,000 to \$30,000 per year for the drug alone. Pharmacogenetic markers predictive of a favorable response would be highly desirable, given the large cost of a therapeutic trial lasting 4 to 6 months. Observations to date suggest that traditional clinical characteristics at baseline cannot reliably predict which patients will have a response to anti-IgE therapy.<sup>114</sup>

## CONCLUSIONS

When asthma symptoms are infrequent, short-lived, and mild, occasional administration of a quick-acting bronchodilator to reverse smooth-muscle constriction in the airways is an acceptable approach. However, as symptoms become more frequent or more severe, the emphasis changes to prevention of symptoms (and of asthmatic attacks) (Fig. 1). By suppressing airway inflammation, an inhaled corticosteroid used once or twice daily reduces the frequency of episodic bronchoconstriction and lessens the risk of asthmatic attacks. In low-to-moderate doses, corticosteroids administered by inhalation are safe for long-term use, even in young children. An alternative to a corticosteroid for mild asthma is a leukotriene-receptor antagonist, which is directed at blocking a specific inflammatory mediator in asthma. Influenza and possibly pneumococcal vaccines are indicated for



patients receiving regular controller therapy for their asthma.<sup>115,116</sup>

When symptoms persist despite medication compliance and good inhalational technique, use of a long-acting  $\beta$ -agonist in combination with an inhaled corticosteroid has proved to be the most effective next step, since it addresses both aspects of airway narrowing in asthma: bronchoconstriction and airway inflammation. A novel option for patients with refractory allergic asthma is therapy with an anti-IgE monoclonal antibody.

Asthma control can often be achieved by increasing the dose of inhaled corticosteroids. However, at high doses, the potential for long-term adverse effects becomes a concern. Thus, once control of asthma has been achieved for a period of 3 to 6 months, efforts should be made to reduce the dose of inhaled corticosteroids to the low-to-moderate range. Use of long-acting  $\beta$ -agonists, leukotriene modifiers, and anti-IgE therapy can facilitate a reduction of the dose of inhaled corticosteroids while maintaining asthma control.

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## REFERENCES

1. The state of asthma in America: Asthma in America survey. (Accessed February 9, 2009, at <http://www.asthmainamerica.com>.)
2. Expert panel report 3: guidelines for the diagnosis and management of asthma. Bethesda, MD: National Heart, Lung, and Blood Institute, August 2007. (NIH publication no. 07-4051.) (Accessed February 9, 2009, at <http://www.nhlbi.nih.gov/guidelines/asthma/asthgdln.pdf>.)
3. Wilson DH, Adams RJ, Tucker G, Appleton S, Taylor AW, Ruffin RE. Trends in asthma prevalence and population changes in South Australia, 1990–2003. *Med J Aust* 2006;184:226-9.
4. Pearce N, Ait-Khaled N, Beasley R, et al. Worldwide trends in the prevalence of asthma symptoms: phase III of the International Study of Asthma and Allergies in Childhood (ISAAC). *Thorax* 2007;62:758-66.
5. Beasley R. The Global Burden of Asthma Report. In: Global Initiative for Asthma (GINA). 2004. (Accessed February 9, 2009, at <http://www.ginasthma.org>.)
6. Epidemiology and Statistics Unit. Trends in asthma morbidity and mortality. New York: American Lung Association, August 2007. (Accessed February 9, 2009, at [http://www.lungusa.org/atf/cf/%7B7A8D42C2-FCCA-4604-8ADE-7F5D5-E762256%7D/TREND\\_ASTMMA2007.PDF](http://www.lungusa.org/atf/cf/%7B7A8D42C2-FCCA-4604-8ADE-7F5D5-E762256%7D/TREND_ASTMMA2007.PDF).)
7. Shore SA. Airway smooth muscle in asthma — not just more of the same. *N Engl J Med* 2004;351:531-2.
8. Johnson PR, Roth M, Tamm M, et al. Airway smooth muscle cell proliferation is increased in asthma. *Am J Respir Crit Care Med* 2001;164:474-7.
9. Azzawi M, Bradley B, Jeffery PK, et al. Identification of activated T lymphocytes and eosinophils in bronchial biopsies in stable atopic asthma. *Am Rev Respir Dis* 1990;142:1407-13.
10. Brightling CE, Bradding P, Symon FA, Holgate ST, Wardlaw AJ, Pavord ID. Mast-cell infiltration of airway smooth muscle in asthma. *N Engl J Med* 2002;346:1699-705.
11. Elias JA, Zhu Z, Chupp G, Homer RJ. Airway remodeling in asthma. *J Clin Invest* 1999;104:1001-6.
12. James AL, Wenzel S. Clinical relevance of airway remodelling in airway diseases. *Eur Respir J* 2007;30:134-55.
13. Global strategy for asthma management and prevention. Global Initiative for Asthma (GINA), 2007. (Accessed February 9, 2009, at <http://www.ginasthma.org>.)
14. Nelson HS.  $\beta$ -Adrenergic bronchodilators. *N Engl J Med* 1995;333:499-506.
15. Lipworth BJ, Struthers AD, McDevitt DG. Tachyphylaxis to systemic but not to airway responses during prolonged therapy with high dose inhaled salbutamol in asthmatics. *Am Rev Respir Dis* 1989;140:586-92.
16. Repsher LH, Anderson JA, Bush RK, et al. Assessment of tachyphylaxis following prolonged therapy of asthma with inhaled albuterol aerosol. *Chest* 1984;85:34-8.
17. Drazen JM, Israel E, Boushey HA, et al. Comparison of regularly scheduled with as-needed use of albuterol in mild asthma. *N Engl J Med* 1996;335:841-7.
18. Israel E, Drazen JM, Liggett SB, et al. The effect of polymorphisms of the beta(2)-adrenergic receptor on the response to regular use of albuterol in asthma. *Am J Respir Crit Care Med* 2000;162:75-80.
19. Israel E, Chinchilli VM, Ford JG, et al. Use of regularly scheduled albuterol treatment in asthma: genotype-stratified, randomised, placebo-controlled cross-over trial. *Lancet* 2004;364:1505-12.
20. Mackay AD, Dyson AJ. How important is the sequence of administration of inhaled beclomethasone dipropionate and salbutamol in asthma? *Br J Dis Chest* 1981;75:273-6.
21. Lawford P, McKenzie D. Pressurized aerosol inhaler technique: how important are inhalation from residual volume, inspiratory flow rate and the time interval between puffs? *Br J Dis Chest* 1983;77:276-81.
22. Salpeter SR, Ormiston TM, Salpeter EE. Cardioselective beta-blockers in patients with reactive airway disease: a meta-analysis. *Ann Intern Med* 2002;137:715-25.
23. Doshan HD, Rosenthal RR, Brown R, Slutsky A, Applin WJ, Caruso FS. Celiprolol, atenolol and propranolol: a comparison of pulmonary effects in asthmatic patients. *J Cardiovasc Pharmacol* 1986;8:Suppl 4:S105-S108.
24. Henderson WR Jr, Banerjee ER, Chi EY. Differential effects of (S)- and (R)-enantiomers of albuterol in a mouse asthma model. *J Allergy Clin Immunol* 2005;116:332-40.
25. Berger WE, Milgrom H, Skoner DP, et al. Evaluation of levalbuterol metered dose inhaler in pediatric patients with asthma: a double-blind, randomized, placebo- and active-controlled trial. *Curr Med Res Opin* 2006;22:1217-26.
26. Hendeles L, Colice GL, Meyer RJ. Withdrawal of albuterol inhalers containing chlorofluorocarbon propellants. *N Engl J Med* 2007;356:1344-51.
27. Ramsdell JW, Colice GL, Ekholm BP, Klinger NM. Cumulative dose response study comparing HFA-134a albuterol sulfate and conventional CFC albuterol in patients with asthma. *Ann Allergy Asthma Immunol* 1998;81:593-9.
28. Newman SP. Spacer devices for metered dose inhalers. *Clin Pharmacokinet* 2004;43:349-60.
29. Cates CJ, Crilly JA, Rowe BH. Holding chambers (spacers) versus nebulizers for beta-agonist treatment of acute asthma. *Cochrane Database Syst Rev* 2006;2:CD000052.
30. Nathan RA. Beta 2 agonist therapy: oral versus inhaled delivery. *J Asthma* 1992;29:49-54.
31. Rebeck AS, Chapman KR, Abboud R, et al. Nebulized anticholinergic and sympathomimetic treatment of asthma and chronic obstructive airways disease in the emergency room. *Am J Med* 1987;82:59-64.
32. Rodrigo GJ, Castro-Rodriguez JA. Anticholinergics in the treatment of children and adults with acute asthma: a systematic review with meta-analysis. *Thorax* 2005;60:740-6. [Errata, *Thorax* 2006;61:274, 458; 2008;63:1029.]
33. Papi A, Canonica GW, Maestrelli P, et al. Rescue use of beclomethasone and albuterol in a single inhaler for mild asthma. *N Engl J Med* 2007;356:2040-52.
34. O'Byrne PM, Bisgaard H, Godard PP, et al. Budesonide/formoterol combination therapy as both maintenance and reliever medication in asthma. *Am J Respir Crit Care Med* 2005;171:129-36.
35. Rabe KF, Atienza T, Magyar P, Larsson P, Jorup C, Lalloo UG. Effect of budesonide in combination with formoterol for reliever therapy in asthma exacerbations: a randomised controlled, double-blind study. *Lancet* 2006;368:744-53.
36. Barnes PJ. How corticosteroids control inflammation: Quintiles Prize Lecture 2005. *Br J Pharmacol* 2006;148:245-54.
37. van der Velden VH. Glucocorticoids: mechanisms of action and anti-inflammatory potential in asthma. *Mediators Inflamm* 1998;7:229-37.
38. Chanez P, Bourdin A, Vachier I, Godard P, Bousquet J, Vignola AM. Effects of inhaled corticosteroids on pathology in asthma and chronic obstructive pulmonary disease. *Proc Am Thorac Soc* 2004;1:184-90.
39. Lundgren R, Söderberg M, Hörstedt P, Stenling R. Morphological studies of bronchial mucosal biopsies from asthmatics before and after ten years of treatment with inhaled steroids. *Eur Respir J* 1988;1:883-9.
40. Feltis BN, Wignarajah D, Reid DW, Ward C, Harding R, Walters EH. Effects of inhaled fluticasone on angiogenesis and vascular endothelial growth factor in asthma. *Thorax* 2007;62:314-9.
41. Haahtela T, Järvinen M, Kava T, et al. Comparison of a  $\beta_2$ -agonist, terbutaline, with an inhaled corticosteroid, budesonide, in newly detected asthma. *N Engl J Med* 1991;325:388-92.
42. Donahue JG, Weiss ST, Livingston JM, Goetsch MA, Greineder DK, Platt R. Inhaled steroids and the risk of hospitalization for asthma. *JAMA* 1997;277:887-91.
43. Suissa S, Ernst P, Benayoun S, Baltzan M, Cai B. Low-dose inhaled corticosteroids and the prevention of death from asthma. *N Engl J Med* 2000;343:332-6.

44. O'Byrne PM, Pedersen S, Lamm CJ, Tan WC, Busse WW. Severe exacerbations and decline in lung function in asthma. *Am J Respir Crit Care Med* 2009;179:19-24.
45. The Childhood Asthma Management Program Research Group. Long-term effects of budesonide or nedocromil in children with asthma. *N Engl J Med* 2000;343:1054-63.
46. Sovijärvi AR, Haahtela T, Ekroos HJ, et al. Sustained reduction in bronchial hyperresponsiveness with inhaled fluticasone propionate within three days in mild asthma: time course after onset and cessation of treatment. *Thorax* 2003;58:500-4.
47. Lazarus SC, Boushey HA, Fahy JV, et al. Long-acting beta2-agonist monotherapy vs continued therapy with inhaled corticosteroids in patients with persistent asthma: a randomized controlled trial. *JAMA* 2001;285:2583-93.
48. Lazarus SC, Chinchilli VM, Rollings NJ, et al. Smoking affects response to inhaled corticosteroids or leukotriene receptor antagonists in asthma. *Am J Respir Crit Care Med* 2007;175:783-90.
49. Tantisira KG, Lake S, Silverman ES, et al. Corticosteroid pharmacogenetics: association of sequence variants in CRHR1 with improved lung function in asthmatics treated with inhaled corticosteroids. *Hum Mol Genet* 2004;13:1353-9.
50. Barnes PJ. Inhaled glucocorticoids for asthma. *N Engl J Med* 1995;332:868-75.
51. Szeffler SJ, Martin RJ, King TS, et al. Significant variability in response to inhaled corticosteroids for persistent asthma. *J Allergy Clin Immunol* 2002;109:410-8.
52. Cumming RG, Mitchell P, Leeder SR. Use of inhaled corticosteroids and the risks of cataracts. *N Engl J Med* 1997;337:8-14.
53. Garbe E, LeLorier J, Boivin JF, Suissa S. Inhaled and nasal glucocorticoids and the risk of ocular hypertension or open-angle glaucoma. *JAMA* 1997;277:722-7.
54. Israel E, Banerjee TR, Fitzmaurice GM, Kotlov TV, LaHive K, LeBoff MS. Effects of inhaled glucocorticoids on bone density in premenopausal women. *N Engl J Med* 2001;345:941-7.
55. Sharek PJ, Bergman DA. The effect of inhaled steroids on the linear growth of children with asthma: a meta-analysis. *Pediatrics* 2000;106(1):e8.
56. Agertoft L, Pedersen S. Effect of long-term treatment with inhaled budesonide on adult height in children with asthma. *N Engl J Med* 2000;343:1064-9.
57. DelGaudio JM. Steroid inhaler laryngitis: dysphonia caused by inhaled fluticasone therapy. *Arch Otolaryngol Head Neck Surg* 2002;128:677-81.
58. Boulet LP, Bateman ED, Voves R, Müller T, Wolf S, Engelstätter R. A randomized study comparing ciclesonide and fluticasone propionate in patients with moderate persistent asthma. *Respir Med* 2007;101:1677-86.
59. Skoner DP, Maspero J, Banerji D, Ciclesonide Pediatric Growth Study Group. Assessment of the long-term safety of inhaled ciclesonide on growth in children with asthma. *Pediatrics* 2008;121(1):e1-e14.
60. Hodges IG, Netherway TA. Once-daily fluticasone propionate is as effective as twice-daily treatment in stable, mild-to-moderate childhood asthma. *Clin Drug Investig* 2005;25:13-22.
61. Jónasson G, Carlsen K-H, Jonasson C, Mowinckel P. Low-dose inhaled budesonide once or twice daily for 27 months in children with mild asthma. *Allergy* 2000;55:740-8.
62. Barnes NC. The properties of inhaled corticosteroids: similarities and differences. *Prim Care Respir J* 2007;16:149-54.
63. Derendorf H, Nave R, Drollmann A, Cerasoli F, Wurst W. Relevance of pharmacokinetics and pharmacodynamics of inhaled corticosteroids to asthma. *Eur Respir J* 2006;28:1042-50.
64. Adams N, Bestall J, Jones PW. Budesonide at different doses for chronic asthma. *Cochrane Database Syst Rev* 2001;4:CD003271.
65. Lemanske RF Jr, Sorkness CA, Mauger EA, et al. Inhaled corticosteroid reduction and elimination in patients with persistent asthma receiving salmeterol: a randomized controlled trial. *JAMA* 2001;285:2594-603.
66. Pearlman DS, Chervinsky P, LaForce C, et al. A comparison of salmeterol with albuterol in the treatment of mild-to-moderate asthma. *N Engl J Med* 1992;327:1420-5.
67. Simons FE, Gerstner TV, Cheang MS. Tolerance to the bronchoprotective effect of salmeterol in adolescents with exercise-induced asthma using concurrent inhaled glucocorticoid treatment. *Pediatrics* 1997;99:655-9.
68. Nelson JA, Strauss L, Skowronski M, Ciuffo R, Novak R, McFadden ER Jr. Effect of long-term salmeterol treatment on exercise-induced asthma. *N Engl J Med* 1998;339:141-6.
69. Weinberger M, Abu-Hasan M. Life-threatening asthma during treatment with salmeterol. *N Engl J Med* 2006;355:852-3.
70. Smyth ET, Pavord ID, Wong CS, Wisniewski AF, Williams J, Tattersfield AE. Interaction and dose equivalence of salbutamol and salmeterol in patients with asthma. *BMJ* 1993;306:543-5.
71. Wechsler ME, Lehman E, Lazarus SC, et al.  $\beta$ -Adrenergic receptor polymorphism and response to salmeterol. *Am J Respir Crit Care Med* 2006;173:519-26.
72. Gibson PG, Powell H, Ducharme FM. Differential effects of maintenance long-acting beta-agonist and inhaled corticosteroid on asthma control and asthma exacerbations. *J Allergy Clin Immunol* 2007;119:344-50.
73. Woolcock A, Lundback B, Ringdal N, Jacques LA. Comparison of addition of salmeterol to inhaled steroids with doubling of the dose of inhaled steroids. *Am J Respir Crit Care Med* 1996;153:1481-8.
74. Pauwels RA, Löfdahl C-G, Postma DS, et al. Effect of inhaled formoterol and budesonide on exacerbations of asthma. *N Engl J Med* 1997;337:1405-11. [Erratum, *N Engl J Med* 1998;338:139.]
75. Gierbycz MA, Kaur M, Leigh R, Newton R. A Holy Grail of asthma management: toward understanding how long-acting  $\beta_2$ -adrenoceptor agonists enhance the clinical efficacy of inhaled corticosteroids. *Br J Pharmacol* 2008;153:1090-104.
76. Nelson HS, Weiss ST, Bleecker ER, Yancey SW, Dorinsky PM, SMART Study Group. The Salmeterol Multicenter Asthma Research Trial: a comparison of usual pharmacotherapy for asthma or usual pharmacotherapy plus salmeterol. *Chest* 2006;129:15-26. [Erratum, *Chest* 2006;129:1393.]
77. Nelson HS. Is there a problem with inhaled long-acting beta-adrenergic agonists? *J Allergy Clin Immunol* 2006;117:3-16.
78. Bateman E, Nelson H, Bousquet J, et al. Meta-analysis: effects of adding salmeterol to inhaled corticosteroids on serious asthma-related events. *Ann Intern Med* 2008;149:33-42.
79. The American Lung Association Asthma Clinical Research Centers. Randomized comparison of strategies for reducing treatment in mild persistent asthma. *N Engl J Med* 2007;356:2027-39. [Erratum, *N Engl J Med* 2007;357:728.]
80. Lötvall J. Pharmacological similarities and differences between beta2-agonists. *Respir Med* 2001;95:Suppl B:S7-S11.
81. Drazen JM, Israel E, O'Byrne PM. Treatment of asthma with drugs modifying the leukotriene pathway. *N Engl J Med* 1999;340:197-206. [Errata, *N Engl J Med* 1999;340:663, 341:1632.]
82. Reiss TF, Chervinsky P, Dockhorn RJ, Shingo S, Seidenberg B, Edwards TB. Montelukast, a once-daily leukotriene receptor antagonist, in the treatment of chronic asthma: a multicenter, randomized, double-blind trial. *Arch Intern Med* 1998;158:1213-20.
83. Knorr B, Matz J, Bernstein JA, et al. Montelukast for chronic asthma in 6- to 14-year-old children: a randomized, double-blind trial. *JAMA* 1998;279:1181-6.
84. Pizzichini E, Leff JA, Reiss TF, et al. Montelukast reduces airway eosinophilic inflammation in asthma: a randomized, controlled trial. *Eur Respir J* 1999;14:12-8.
85. Minoguchi K, Kohno Y, Minoguchi H, et al. Reduction of eosinophilic inflammation in the airways of patients with asthma using montelukast. *Chest* 2002;121:732-8.

86. Boushey HA, Sorkness CA, King TS, et al. Daily versus as-needed corticosteroids for mild persistent asthma. *N Engl J Med* 2005;352:1519-28.
87. Pajaron-Fernandez M, Garcia-Rubia S, Sanchez-Solis M, Garcia-Marcos L. Montelukast administered in the morning or evening to prevent exercise-induced bronchoconstriction in children. *Pediatr Pulmonol* 2006;41:222-7.
88. Dahlén B, Nizankowska E, Szczeklik A, et al. Benefits from adding the 5-lipoxygenase inhibitor zileuton to conventional therapy in aspirin-intolerant asthmatics. *Am J Respir Crit Care Med* 1998;157:1187-94.
89. Wechsler ME, Finn D, Gunawardena D, et al. Churg-Strauss syndrome in patients receiving montelukast as treatment for asthma. *Chest* 2000;117:708-13.
90. Wechsler ME, Drazen JM. Zafirlukast and Churg-Strauss syndrome. *Chest* 1999;116:266-7.
91. Wechsler ME, Pauwels R, Drazen JM. Leukotriene modifiers and Churg-Strauss syndrome: adverse effect or response to corticosteroid withdrawal? *Drug Saf* 1999;21:241-51.
92. Hauser T, Mahr A, Metzler C, et al. The leukotriene-receptor antagonist montelukast and the risk of Churg-Strauss syndrome: a case-crossover study. *Thorax* 2008;63:677-82.
93. Nathani N, Little MA, Kunst H, Wilson D, Thickett DR. Churg-Strauss syndrome and leukotriene antagonist use: a respiratory perspective. *Thorax* 2008;63:883-8.
94. Food and Drug Administration, Center for Drug Evaluation and Research. Update of safety review: follow-up to the March 27, 2008, communication about the ongoing safety review of montelukast (Singulair). (Accessed February 9, 2009, at [http://www.fda.gov/cder/drug/early\\_comm/montelukast\\_200901.htm](http://www.fda.gov/cder/drug/early_comm/montelukast_200901.htm).)
95. Israel E, Rubin P, Kemp JP, et al. The effect of inhibition of 5-lipoxygenase by zileuton in mild-to-moderate asthma. *Ann Intern Med* 1993;119:1059-66.
96. Malmström K, Rodriguez-Gomez G, Guerra J, et al. Oral montelukast, inhaled beclomethasone, and placebo for chronic asthma: a randomized, controlled trial. *Ann Intern Med* 1999;130:487-95.
97. Peters-Golden M, Swern A, Bird SS, Hustad CM, Grant E, Edelman JM. Influence of body mass index on the response to asthma controller agents. *Eur Respir J* 2006;27:495-503.
98. Kim SH, Ye YM, Hur GY, et al. CysLTR1 promoter polymorphism and requirement for leukotriene receptor antagonist in aspirin-intolerant asthma patients. *Pharmacogenomics* 2007;8:1143-50.
99. Dahlén SE, Malmström K, Nizankowska E, et al. Improvement of aspirin-intolerant asthma by montelukast, a leukotriene antagonist: a randomized, double-blind, placebo-controlled trial. *Am J Respir Crit Care Med* 2002;165:9-14.
100. Lima JJ, Zhang S, Grant A, et al. Influence of leukotriene pathway polymorphisms on response to montelukast in asthma. *Am J Respir Crit Care Med* 2006;173:379-85.
101. Brabson JH, Clifford D, Kerwin E, et al. Efficacy and safety of low-dose fluticasone propionate compared with zafirlukast in patients with persistent asthma. *Am J Med* 2002;113:15-21.
102. Sorkness CA, Lemanske RF Jr, Mauger DT, et al. Long-term comparison of 3 controller regimens for mild-moderate persistent childhood asthma: the Pediatric Asthma Controller Trial. *J Allergy Clin Immunol* 2007;119:64-72. [Erratum, *J Allergy Clin Immunol* 2007;120:285.]
103. Ostrom NK, Decotiis BA, Lincourt WR, et al. Comparative efficacy and safety of low-dose fluticasone propionate and montelukast in children with persistent asthma. *J Pediatr* 2005;147:213-20.
104. Price DB, Hernandez D, Magyar P, et al. Randomised controlled trial of montelukast plus inhaled budesonide versus double dose inhaled budesonide in adult patients with asthma. *Thorax* 2003;58:211-6.
105. Simons FE, Villa JR, Lee BW, et al. Montelukast added to budesonide in children with persistent asthma: a randomized, double-blind, crossover study. *J Pediatr* 2001;138:694-8.
106. Ducharme FM, Lasserson TJ, Cates CJ. Long-acting beta2-agonists versus anti-leukotrienes as add-on therapy to inhaled corticosteroids for chronic asthma. *Cochrane Database Syst Rev* 2006;4:CD003137.
107. Deykin A, Wechsler ME, Boushey HA, et al. Combination therapy with a long-acting beta-agonist and a leukotriene antagonist in moderate asthma. *Am J Respir Crit Care Med* 2007;175:228-34.
108. Milgrom H, Fick RB Jr, Su JQ, et al. Treatment of allergic asthma with monoclonal anti-IgE antibody. rhuMab-E25 Study Group. *N Engl J Med* 1999;341:1966-73.
109. Prussin C, Griffith DT, Boesel KM, Lin H, Foster B, Casale TB. Omalizumab treatment downregulates dendritic cell FcεpsilonR1 expression. *J Allergy Clin Immunol* 2003;112:1147-54.
110. Cox L, Platts-Mills TAE, Finegold I, Schwartz LB, Simons FER, Wallace DV. American Academy of Allergy, Asthma & Immunology/American College of Allergy, Asthma and Immunology Joint Task Force report on omalizumab-associated anaphylaxis. *J Allergy Clin Immunol* 2007;120:1373-7.
111. Humbert M, Beasley R, Ayres J, et al. Benefits of omalizumab as add-on therapy in patients with severe persistent asthma who are inadequately controlled despite best available therapy (GINA 2002 step 4 treatment): INNOVATE. *Allergy* 2005;60:309-16.
112. Busse W, Corren J, Lanier BQ, et al. Omalizumab, anti-IgE recombinant humanized monoclonal antibody, for the treatment of severe allergic asthma. *J Allergy Clin Immunol* 2001;108:184-90.
113. Solèr M, Matz J, Townley R, et al. The anti-IgE antibody omalizumab reduces exacerbations and steroid requirement in allergic asthmatics. *Eur Respir J* 2001;18:254-61. [Erratum, *Eur Respir J* 2001;18:739-40.]
114. Bousquet J, Rabe K, Humbert M, et al. Predicting and evaluating response to omalizumab in patients with severe allergic asthma. *Respir Med* 2007;101:1483-92.
115. The American Lung Association Asthma Clinical Research Centers. The safety of inactivated influenza vaccine in adults and children with asthma. *N Engl J Med* 2001;345:1529-36.
116. Talbot TR, Hartert TV, Mitchel E, et al. Asthma as a risk factor for invasive pneumococcal disease. *N Engl J Med* 2005;352:2082-90.

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**CORRECTION**

**Drug Therapy: Asthma**

Drug Therapy: Asthma . Throughout the second row of Table 2 (Budesonide) (page 1006), and in the paragraph beginning with “There are differences,” near the end of the section on Inhaled Corticosteroids (page 1007), the phrase “solution for nebulization” should have read “suspension for nebulization.” The article has been corrected at NEJM.org.