Oral and Injectable (Non-Insulin) Pharmacological Agents for Type 2 Diabetes

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ABSTRACT

While lifestyle changes such as dietary modification and increased physical activity can be very effective in improving glycemic control, over the long-term most individuals with Type 2 diabetes will require medications to achieve glycemic control. The purpose of this chapter is to provide the healthcare practitioner with an overview of the existing oral and injectable (non-insulin) pharmacological options available for the treatment of patients with Type 2 diabetes. Currently, there are nine classes of orally available pharmacological agents to treat Type 2 diabetes: 1) sulfonylureas, 2) meglitinides, 3) metformin (a biguanide), 4) thiazolidinediones (TZDs), 5) alpha glucosidase inhibitors, 6) dipeptidyl peptidase IV (DPP-4) inhibitors, 7) bile acid sequestrants, 8) dopamine agonists, and 9) sodium-glucose transport protein 2 (SGLT2) inhibitors. In addition, glucagon like peptide 1 (GLP-1) receptor agonists and amylin can be administered by injection. Medications from these distinct classes of pharmaceutical agents may be used as treatment by themselves (monotherapy) or in a combination of 2 or more drugs from multiple classes with different mechanisms of action. A variety of fixed combination of 2 agents are available in the US and in many other countries. In this chapter we discuss the administration, mechanism of action, effect on glycemic control, other benefits, side effects, and the contraindications of the use of these glucose lowering drugs.

INTRODUCTION

While lifestyle changes such as dietary modification and increased physical activity can be very effective in improving glycemic control, over the long-term most individuals with Type 2 diabetes will require medications to achieve glycemic control (1). The purpose of this chapter is to provide the healthcare practitioner with an overview of the existing oral and injectable (non-insulin) pharmacological options available for the treatment of patients with Type 2 diabetes. The use of these drugs to treat diabetes during pregnancy, in children and adolescents, and for the prevention of diabetes are discussed in other Endotext chapters (2-4). For information on the management of Type 2 diabetes and selecting amongst the available pharmacological agents see the chapter by Cavaiola and Pettus in Endotext (5).

Currently, there are nine classes of orally available pharmacological agents to treat Type 2 diabetes: 1) sulfonylureas, 2) meglitinides, 3) metformin (a biguanide), 4) thiazolidinediones (TZDs), 5) alpha glucosidase inhibitors, 6) dipeptidyl peptidase IV (DPP-4) inhibitors, 7) bile acid sequestrants, 8) dopamine agonists, and 9) sodium-glucose transport protein 2 (SGLT2) inhibitors (Table 1) (6-8). In addition, glucagon like peptide 1 (GLP-1) receptor agonists and amylin can be administered by injection (Table 2) (6-8).
<table>
<thead>
<tr>
<th>General Class</th>
<th>Compound/Brand Name</th>
<th>Available</th>
<th>Dose Range</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Generation Sulfonylureas</td>
<td>Chlorpropamide/ Diabinese</td>
<td>Yes</td>
<td>100-750mg qd</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Tolazamide/ Tolinase</td>
<td>Yes</td>
<td>100mg qd to 500mg bid</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Tolbutamide/ Orinase</td>
<td>Yes</td>
<td>500mg qd to 1000mg tid with meals</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Acetohexamide/ Dymelor</td>
<td>Yes</td>
<td>250mg qd to 750mg bid</td>
<td>Low</td>
</tr>
<tr>
<td>2nd Generation Sulfonylureas</td>
<td>Glyburide (Glibenclamide)/ Diabeta, Glynase</td>
<td>Yes</td>
<td>2.5mg qd to 10mg bid</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Glipizide/ Glucotrol, Glucotrol XL</td>
<td>Yes</td>
<td>2.5mg qd to 20mg bid</td>
<td>Low</td>
</tr>
<tr>
<td>Meglitinides</td>
<td>Glimepiride/ Amaryl</td>
<td>Yes</td>
<td>0.5mg to 8mg qd</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Repaglinide/ Prandin</td>
<td>Yes</td>
<td>0.5mg to 4 mg with meals. Max 16mg/day</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Nateglinide/ Starlix</td>
<td>Yes</td>
<td>60-120mg tid with meals</td>
<td>Low</td>
</tr>
<tr>
<td>Biguanide</td>
<td>Metformin/ Glucophage, Glucophage XR</td>
<td>Yes</td>
<td>500-2500mg qd or tid depending upon preparation</td>
<td>Low</td>
</tr>
<tr>
<td>Thiazolidinediones (TZDs)</td>
<td>Rosiglitazone/ Avandia</td>
<td>Yes</td>
<td>4-8mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Pioglitazone/ Actos</td>
<td>Yes</td>
<td>15-45mg qd</td>
<td>Low</td>
</tr>
<tr>
<td>Alpha-glucosidase inhibitors</td>
<td>Acarbose/ Precose</td>
<td>Yes</td>
<td>25-100mg tid with meals</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Miglitol/ Glyset</td>
<td>Yes</td>
<td>25-100mg tid with meals</td>
<td>High</td>
</tr>
<tr>
<td>Dipeptidyl peptidase-IV (DPP-4) inhibitors</td>
<td>Alogliptin/ Nesina</td>
<td>Yes</td>
<td>25mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Linagliptin/ Tradjenta</td>
<td>No</td>
<td>5mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Sitagliptin/ Januvia</td>
<td>No</td>
<td>25-100mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Saxagliptin/ Onglyza</td>
<td>No</td>
<td>2.5-5mg qd</td>
<td>High</td>
</tr>
<tr>
<td>Bile Acid Sequestrant</td>
<td>Colesevelam/ Welchol</td>
<td>No</td>
<td>1875mg bid or 3.75-gram packet or bar qd</td>
<td>High</td>
</tr>
<tr>
<td>Dopamine Agonist</td>
<td>Bromocriptine/ Cycloset</td>
<td>No</td>
<td>0.8 - 4.8mg qAM</td>
<td>High</td>
</tr>
<tr>
<td>Sodium-glucose co-transporter-2 (SGLT2) inhibitors</td>
<td>Canagliflozin/ Invokana</td>
<td>No</td>
<td>100-300mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Dapagliflozin/ Farxiga</td>
<td>No</td>
<td>5-10mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Empagliflozin/ Jardiance</td>
<td>No</td>
<td>10-25mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Ertugliflozin/ Stelgatro</td>
<td>No</td>
<td>5-15mg qd</td>
<td>High</td>
</tr>
</tbody>
</table>
Table 2. Currently Available (USA) Injectable Hypoglycemic Drugs to Treat Type 2 Diabetes

<table>
<thead>
<tr>
<th>General Class</th>
<th>Compound/Brand Name</th>
<th>Generic Available</th>
<th>Dose Range</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLP-1 Receptor Agonist (Incretin Mimetic)</td>
<td>Exenatide/ Byetta</td>
<td>No</td>
<td>5-10mcg bid</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Exenatide/ Bydureon</td>
<td>No</td>
<td>2mg once weekly</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Liraglutide/ Victoza</td>
<td>No</td>
<td>0.6-1.8mg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Albigrutide/ Tanzeum*</td>
<td>No</td>
<td>30-50mg once weekly</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Dulaglutide/ Trulicity</td>
<td>No</td>
<td>0.75-1.5mg once weekly</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Lixisenatide/ Adlyxin</td>
<td>No</td>
<td>10-20mcg qd</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Semaglutide/ Ozempic</td>
<td>No</td>
<td>0.25-1.0mg once weekly</td>
<td>High</td>
</tr>
<tr>
<td>Amylin Mimetic</td>
<td>Pramlintide/ Symlin</td>
<td>No</td>
<td>15-120mcg tid with meals</td>
<td>High</td>
</tr>
</tbody>
</table>

*Withdrawn from market

Medications from these distinct classes of pharmaceutical agents may be used as treatment by themselves (monotherapy) or in a combination of 2 or more drugs from multiple classes with different mechanisms of action (6,7). A variety of fixed combination of 2 agents are available in the US and in many other countries (Table 3). There is even a combination that contains 3 drugs (Qternmet XR which contains dapagliflozin, saxagliptin, and metformin). Additionally, there are combinations of GLP-1 receptor agonists and insulin (Table 3). These combination products may be useful and attractive to the patient, as they provide two drugs in a single tablet or injection, offering convenience and increased compliance. In the US, they also enable patients to receive two medications for a single medical insurance co-payment. Most importantly, the addition of a second drug results in an additive improvement in glycemic control. When a patient is on drug A if drug B is added to drug A, there is an improvement in glycemic control. This concept can be extended by the addition of a third drug C, and even a fourth drug D (Figure 1).
<table>
<thead>
<tr>
<th>Drug 1</th>
<th>Drug 2</th>
<th>Brand Name</th>
<th>Generic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glyburide</td>
<td>Metformin</td>
<td>Glucovance (discontinued by manufacturer; generic available)</td>
<td>Yes</td>
</tr>
<tr>
<td>Glipizide</td>
<td>Metformin</td>
<td>Metaglip (discontinued by manufacturer; generic available)</td>
<td>Yes</td>
</tr>
<tr>
<td>Glimepiride</td>
<td>Pioglitazone</td>
<td>Duetact</td>
<td>Yes</td>
</tr>
<tr>
<td>Glimepiride</td>
<td>Rosiglitazone</td>
<td>Avandaryl</td>
<td>Yes</td>
</tr>
<tr>
<td>Sitagliptin</td>
<td>Metformin</td>
<td>Janumet</td>
<td>No</td>
</tr>
<tr>
<td>Saxagliptin</td>
<td>Metformin</td>
<td>Kombiglyze XR</td>
<td>No</td>
</tr>
<tr>
<td>Pioglitazone</td>
<td>Metformin</td>
<td>ACTOSplus Met; ACTOSplus Met XR</td>
<td>Yes</td>
</tr>
<tr>
<td>Repaglinide</td>
<td>Metformin</td>
<td>PrandiMet</td>
<td>Yes</td>
</tr>
<tr>
<td>Rosiglitazone</td>
<td>Metformin</td>
<td>Avandamet</td>
<td>Yes</td>
</tr>
<tr>
<td>Linagliptin</td>
<td>Metformin</td>
<td>Jentadueto</td>
<td>No</td>
</tr>
<tr>
<td>Alogliptin</td>
<td>Metformin</td>
<td>Kazano</td>
<td>Yes</td>
</tr>
<tr>
<td>Alogliptin</td>
<td>Pioglitazone</td>
<td>Oseni</td>
<td>No</td>
</tr>
<tr>
<td>Canagliflozin</td>
<td>Metformin</td>
<td>Invokamet</td>
<td>No</td>
</tr>
<tr>
<td>Dapagliflozin</td>
<td>Metformin</td>
<td>Xigduo XR</td>
<td>No</td>
</tr>
<tr>
<td>Dapagliflozin</td>
<td>Saxagliptin</td>
<td>Qtern</td>
<td>No</td>
</tr>
<tr>
<td>Empagliflozin</td>
<td>Linagliptin</td>
<td>Glyxambi</td>
<td>No</td>
</tr>
<tr>
<td>Empagliflozin</td>
<td>Metformin</td>
<td>Synjardy</td>
<td>No</td>
</tr>
<tr>
<td>Ertugliflozin</td>
<td>Metformin</td>
<td>Segluromet</td>
<td>No</td>
</tr>
<tr>
<td>Ertugliflozin</td>
<td>Sitagliptin</td>
<td>StegluJan</td>
<td>No</td>
</tr>
<tr>
<td>Lixisenatide</td>
<td>Glargine Insulin</td>
<td>Soliqua</td>
<td>No</td>
</tr>
<tr>
<td>Liraglutide</td>
<td>Degludec Insulin</td>
<td>Xultophy</td>
<td>No</td>
</tr>
</tbody>
</table>
Figure 1. Efficacy When Oral Agents are Used as Add-On Therapy. When a patient is on drug A and they are changed to drug B, C, or D, often no improvement in glucose control will be seen. However, if drug B is added to drug A, there is an improvement. This concept can often be extended by the addition of a third drug (C), or even a fourth drug (D). There is decreasing benefit for each additional drug as the baseline A1c level decreases. Note that there is limited data on the use of 4 drug combinations.

OVERVIEW OF DRUGS

There are a number of different abnormalities that contribute to the hyperglycemia that occurs in patients with Type 2 diabetes (9). Therefore, the drugs used to treat patients with Type 2 diabetes can have a number of different mechanisms by which they lower glucose levels. Figure 2 shows the various sites of action of the pharmacological therapies for the treatment of Type 2 diabetes.
Figure 2. Sites of Action of Pharmacological Therapies for the Treatment of Type 2 Diabetes.

A broad overview of the most commonly used drugs to treat Type 2 diabetes is shown in Table 4 and the effect of drugs on blood lipid levels is shown in Table 5.
### Table 4: Benefits and Side Effects of Commonly Used Drugs

<table>
<thead>
<tr>
<th>Drugs</th>
<th>Ability to Lower Glucose</th>
<th>Risk of Hypoglycemia</th>
<th>Weight Change</th>
<th>Effect on ASCVD</th>
<th>Effect on CHF</th>
<th>Effect on Renal Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd Generation SU</td>
<td>High</td>
<td>Yes</td>
<td>Increase</td>
<td>Neutral</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>Metformin</td>
<td>High</td>
<td>No</td>
<td>Neutral-modest weight loss</td>
<td>Potential Benefit</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>TZDs</td>
<td>High</td>
<td>No</td>
<td>Increase</td>
<td>Potential Benefit (Pioglitazone)</td>
<td>Increased</td>
<td>Neutral</td>
</tr>
<tr>
<td>DPP-4 inhibitors</td>
<td>Intermediate</td>
<td>No</td>
<td>Neutral</td>
<td>Potential Increase (saxagliptin and alogliptin)</td>
<td>Neutral</td>
<td>Neutral</td>
</tr>
<tr>
<td>SGLT2 inhibitors</td>
<td>Immediate-High</td>
<td>No</td>
<td>Decrease</td>
<td>Neutral</td>
<td>Benefit</td>
<td>Benefit-Reduced progression of renal failure</td>
</tr>
<tr>
<td>GLP-1 receptor agonists</td>
<td>High</td>
<td>No</td>
<td>Decrease</td>
<td>Benefit</td>
<td>Neutral</td>
<td>Benefit-Decreased proteinuria</td>
</tr>
</tbody>
</table>

### Table 5: Effect of Glucose Lowering Drugs on Lipid Levels*

<table>
<thead>
<tr>
<th>Drugs</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metformin</td>
<td>Decrease triglycerides and modestly decrease LDLc</td>
</tr>
<tr>
<td>Sulfonylureas</td>
<td>No effect</td>
</tr>
<tr>
<td>Meglitinides</td>
<td>No effect</td>
</tr>
<tr>
<td>DPP-4 inhibitors</td>
<td>Decrease postprandial triglycerides</td>
</tr>
<tr>
<td>GLP1 receptor agonists</td>
<td>Decrease fasting and postprandial triglycerides and increase HDLc</td>
</tr>
<tr>
<td>Acarbose</td>
<td>Decrease postprandial triglycerides</td>
</tr>
<tr>
<td>Thiazolidinediones</td>
<td>Decrease triglycerides and increase HDLc. Small increase LDLc but a decrease in small dense LDL</td>
</tr>
<tr>
<td>SGLT2 inhibitors</td>
<td>Small increase in LDLc and HDLc</td>
</tr>
<tr>
<td>Colesevelam</td>
<td>Decrease LDLc, may increase triglycerides</td>
</tr>
<tr>
<td>Bromocriptine-QR</td>
<td>Decrease triglycerides</td>
</tr>
</tbody>
</table>

*These effects are beyond benefits of glucose lowering
Bloomgarden et al reported results from a meta-regression analysis of 61 clinical trials evaluating the efficacy of the five major classes of oral anti-hyperglycemic agents (10). The results demonstrated that there is a strong direct correlation between baseline A1c level and the magnitude of the decrease in fasting glucose and A1c induced by these drugs (i.e. significantly greater reductions in both fasting plasma glucose and A1c were observed in groups with higher baseline A1c levels). For those patients whose A1c was <8.0%, the reduction in A1c that resulted from drug therapy was only 0.1-0.2%. These results are presented graphically in Figure 3. Thus, expectations for the overall magnitude of effect from a given agent might be very modest when treating patients whose baseline A1c is <7.5-8.0% while in patients with elevated A1c levels the effect of drug therapy may be very robust. A separate meta-analysis of 59 clinical studies reached similar conclusions (11). These results indicate that comparing efficacies among different anti-diabetic medications is challenging, when the baseline HbA1c is different in the studies being compared.

Additionally, the population of patients studied can impact the efficacy of a particular class of drug. For example, patients with limited beta cell function will have a decreased response to sulfonylurea drugs as these agents work via stimulating insulin secretion by the beta cells while TZDs are most effective in patients with insulin resistance. Another example would be the decrease in efficacy of SGLT2 inhibitors in patients with decreased renal function. It is thus very difficult to compare the glucose lowering effects of different hypoglycemic drugs.

![Figure 3. Relationship between baseline A1c level and the observed reduction in A1c with oral anti-hyperglycemic medications. Irrespective of drug class, the baseline glycemic control markedly influences the overall magnitude of efficacy. Data from Bloomgarden et al, Table 1 (10).](image-url)

A recent model-based meta-analysis was used to compare glycemic control between a large number of drugs adjusted for important differences between studies, including duration of treatment, baseline glycated hemoglobin, and drug dosages (12). In this analysis 229 studies with 121,914 patients were utilized. Table 6 shows the estimated decrease in A1c levels for different drugs in patients that are drug naïve with an A1c of 8% and a weight of 90kg after 26 weeks of treatment. If one averages the effect on A1c of the highest doses for each drug in a specific drug class the reductions in A1c for each class of drug are metformin 1.09%, sulfonylureas 1.0%, TZDs 0.95%, DPP-4 inhibitors 0.66%, SGLT2 inhibitors 0.83%, and GLP-1 receptor agonists 1.24%. These data and the individual data for each drug in table 6 provides a rough estimate of the efficacy of various drugs and drug classes in lowering A1c levels. One should note that within a drug class there may be differences in the ability of different drugs to lower A1c levels. This is particularly true with the GLP-1 receptor agonist drugs.
Table 6. Estimated Efficacy of Hypoglycemic Drugs Available in US (12)

<table>
<thead>
<tr>
<th>Drug</th>
<th>A1c Decrease</th>
<th>Drug</th>
<th>A1c Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metformin 2000mg</td>
<td>1.01</td>
<td>Dulaglutide 0.75</td>
<td>1.18</td>
</tr>
<tr>
<td>Metformin 2550mg</td>
<td>1.09</td>
<td>Dulaglutide 1.5mg</td>
<td>1.36</td>
</tr>
<tr>
<td>Glipizide 5-20mg</td>
<td>0.86</td>
<td>Exenatide 10ug BID</td>
<td>0.86</td>
</tr>
<tr>
<td>Glyburide 1.25-20mg</td>
<td>1.17</td>
<td>Exenatide 2mg QW</td>
<td>1.16</td>
</tr>
<tr>
<td>Glimepiride 1-8mg</td>
<td>0.97</td>
<td>Exenatide 2mg QWS</td>
<td>1.14</td>
</tr>
<tr>
<td>Pioglitazone 15mg</td>
<td>0.62</td>
<td>Liraglutide 0.6mg</td>
<td>0.88</td>
</tr>
<tr>
<td>Pioglitazone 30mg</td>
<td>0.85</td>
<td>Liraglutide 1.2mg</td>
<td>1.13</td>
</tr>
<tr>
<td>Pioglitazone 45mg</td>
<td>0.98</td>
<td>Liraglutide 1.8mg</td>
<td>1.25</td>
</tr>
<tr>
<td>Rosiglitazone 4mg</td>
<td>0.67</td>
<td>Lixisenatide 10ug</td>
<td>0.44</td>
</tr>
<tr>
<td>Rosiglitazone 8mg</td>
<td>0.91</td>
<td>Lixisenatide 20ug</td>
<td>0.66</td>
</tr>
<tr>
<td>Canagliflozin 100mg</td>
<td>0.84</td>
<td>Semaglutide 0.5mg</td>
<td>1.43</td>
</tr>
<tr>
<td>Canagliflozin 300mg</td>
<td>1.01</td>
<td>Semaglutide 1.0mg</td>
<td>1.77</td>
</tr>
<tr>
<td>Dapagliflozin 5mg</td>
<td>0.65</td>
<td>Alogliptin 12.5mg</td>
<td>0.58</td>
</tr>
<tr>
<td>Dapagliflozin 10mg</td>
<td>0.73</td>
<td>Alogliptin 25mg</td>
<td>0.66</td>
</tr>
<tr>
<td>Empagliflozin 10mg</td>
<td>0.69</td>
<td>Linagliptin 5mg</td>
<td>0.59</td>
</tr>
<tr>
<td>Empagliflozin 25mg</td>
<td>0.77</td>
<td>Saxagliptin 2.5mg</td>
<td>0.59</td>
</tr>
<tr>
<td>Ertugliflozin 5mg</td>
<td>0.73</td>
<td>Saxagliptin 5mg</td>
<td>0.67</td>
</tr>
<tr>
<td>Ertugliflozin 15mg</td>
<td>0.81</td>
<td>Sitagliptin 100mg</td>
<td>0.72</td>
</tr>
</tbody>
</table>

The decreases in A1c are modeled for drug naïve patients with an A1c of 8% and a weight of 90kg after 26 weeks of treatment.

The NIH is carrying out a study, Glycemia Reduction Approaches in Diabetes: A Comparative Effectiveness (GRADE) Study, that is randomizing 5,000 patients on metformin therapy to sulfonylureas, DPP-4 inhibitors, GLP-1 receptor agonists, and insulin (13). The primary outcome is the time to primary failure defined as an A1c ≥ 7% over an anticipated mean observation period of 4.8 years (range 4-7 years). This study will provide additional information on the relative effectiveness of various hypoglycemic drugs. It should be noted that the SGLT2 inhibitor and TZD drugs are not included in this study.

SULFONYLUREAS

Introduction

Sulfonylureas were developed in the 1950s and have been widely used in the treatment of patients with Type 2 diabetes (14,15). First generation sulfonylureas (acetohexamide, chlorpropamide, tolazamide, and tobutamide) possess a lower binding affinity for the ATP-sensitive potassium channel, their molecular target (vide infra), and thus require higher doses to achieve efficacy (see table 1) (14,15). These first-generation sulfonylureas are currently rarely used. Subsequently, in the 1980s 2nd generation sulfonylureas including glyburide (glibenclamide), glipizide, and glimepiride were developed and are now widely used (14). The 2nd generation sulfonylureas are much more potent compounds (~100-fold). Sulfonylureas can be used as monotherapy or in combination with any other class of oral diabetic medications except meglitinides (8,14).

Key characteristics of the different sulfonylureas are shown in Table 7 (14). Of clinical importance is the duration of action, which varies with the rate of hepatic metabolism and the hypoglycemic activity of the metabolites. Drugs with a long duration of action are more likely to cause severe and prolonged hypoglycemia whereas short acting drugs need to be given multiple times per day (14). Additionally, drugs that are metabolized to active agents (for example glyburide) are also more likely to cause hypoglycemia (14). Most sulfonylureas are metabolized in the liver and are to some extent excreted by the kidney; therefore, hepatic and/or renal impairment increases the risk of hypoglycemia (14).
## Table 7. Key Characteristics of Sulfonylureas

<table>
<thead>
<tr>
<th>Drug</th>
<th>Duration of action</th>
<th>Metabolites</th>
<th>Excretion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolbutamide</td>
<td>6–12 h</td>
<td>Inactive</td>
<td>Kidney</td>
</tr>
<tr>
<td>Chlorpropamide</td>
<td>60 h</td>
<td>Active or unchanged</td>
<td>Kidney</td>
</tr>
<tr>
<td>Tolazamide</td>
<td>12–24 h</td>
<td>Inactive</td>
<td>Kidney</td>
</tr>
<tr>
<td>Glipizide</td>
<td>12–24 h</td>
<td>Inactive</td>
<td>Kidney 80%</td>
</tr>
<tr>
<td>Glipizide ER</td>
<td>&gt;24 h</td>
<td>Inactive</td>
<td>Kidney 80%</td>
</tr>
<tr>
<td>Glyburide</td>
<td>16–24 h</td>
<td>Inactive or weakly</td>
<td>Kidney 50%</td>
</tr>
<tr>
<td>Micronized glyburide</td>
<td>12-24 h</td>
<td>Inactive or weakly</td>
<td>Kidney 50%</td>
</tr>
<tr>
<td>Glimepiride</td>
<td>24 h</td>
<td>Inactive or weakly</td>
<td>Kidney 60%</td>
</tr>
</tbody>
</table>

### Administration

Sulfonylureas should be taken 30 minutes before meals starting with a low dose with an increase in dosage until desired glycemic control has been achieved. In patients with a high risk of severe hypoglycemia a very low-dose can be the initial therapy while in patients with high A1c levels one can initiate therapy at a higher dose.

The recommended starting dose of glipizide is 5 mg approximately 30 minutes before breakfast. Geriatric patients or those with liver or renal disease or other risk factors for severe hypoglycemia can be started on 2.5 mg. Patients with very high A1c levels may be started on a higher dose. Based on the glucose response the dose can be increased weekly by 2.5-5 mg. If a once a day dose is not satisfactory or the patient requires more than 15 mg per day one can give the drug before breakfast and dinner. The maximum daily dose is 40 mg per day.

The usual starting dose of extended release glipizide is 5 mg per day with breakfast. Those patients who are at high risk of hypoglycemia may be started at a lower dose. The dose can be increased based on glucose or A1c measurements. The maximum dose is 20 mg per day.

The usual starting dose of glyburide is 2.5 to 5 mg daily with breakfast or the first main meal. Patients at high risk for hypoglycemia should be started on 1.25 mg per day. The dose should be increased weekly by 2.5 mg based on the glucose response. The maximum dose per day is 20 mg.

The usual starting dose of micronized glyburide is 1.5 to 3 mg daily with breakfast or the first main meal. Patients at high risk for hypoglycemia should be started on 0.75 mg per day. The dose should be increased weekly by 1.5 mg based on the glucose response. The maximum dose per day is 12 mg.

The recommended starting dose of glimepiride is 1 or 2 mg once daily. Patients at increased risk for hypoglycemia should be started on 1mg once daily. The dose should be increased every 1-2 weeks in increments of 1 or 2 mg based upon the patient’s glycemic response. The maximum dose is 8 mg per day.

### Mechanism of Action

Sulfonylureas are insulin secretagogues and lower blood glucose levels by directly stimulating glucose independent insulin secretion by the pancreatic beta cells (8,14). Through the concerted efforts of GLUT2 (the high Km glucose transporter), glucokinase (the enzyme that phosphorylates glucose), and glucose metabolism, pancreatic beta cells sense blood glucose levels and secrete the appropriate amount of insulin in response (16,17). Glucose metabolism leads to ATP generation and increases the intracellular ratio of ATP/ADP, which results in the closure of the ATP-sensitive potassium channel on the plasma membrane (14,16,18). Closure of this channel depolarizes the membrane and triggers the opening of voltage-
Sensitive calcium channels, leading to the rapid influx of calcium (14,19). Increased intracellular calcium causes an alteration in the cytoskeleton and stimulates translocation of insulin-containing secretory granules to the plasma membrane and the secretion of insulin (Figure 4) (14).

**Figure 4. Mechanism by which glucose, sulfonylureas, and meglitinides stimulate insulin secretion by the beta cells.**

The KATP channel is comprised of two subunits, both of which are required for the channel to be functional (19). One subunit contains the cytoplasmic binding sites for both sulfonylureas and ATP, and is designated as the sulfonylurea receptor type 1 (SUR1). The other subunit is the potassium channel, which acts as the pore-forming subunit (19). Either an increase in the ATP/ADP ratio or ligand binding by sulfonylureas or meglitinides to SUR1 results in the closure of the KATP channel and insulin secretion (15,19). Studies comparing sulfonylureas and non-sulfonylurea insulin secretagogues have identified several distinct binding sites on the SUR1 that cause channel closure. Some sites exhibit high affinity for sulfonylureas, while other sites exhibit high affinity for meglitinides.

In addition to binding to SUR1, sulfonylureas also bind to Epac2, a protein activated by cAMP (14). Sulfonylurea-stimulated insulin secretion was reduced both in vitro and in vivo in mice lacking Epac2, indicating that Epac2 also plays a role in sulfonylurea induced insulin secretion (20).

In addition to inducing insulin secretion sulfonylureas have other effects that could play a role in lowering blood glucose levels (14). Specifically, sulfonylureas have been shown to decrease hepatic insulin clearance, inhibit glucagon secretion from pancreatic alpha-cells (this may be secondary to increasing insulin secretion), and enhance insulin sensitivity in peripheral tissues (this may be partially due to lowering glucose levels and reducing glucotoxicity) (14). The contribution and importance of these additional effects in mediating the glucose lowering effects of sulfonylureas is uncertain.

**Glycemic Efficacy**

When used at maximally effective doses, results from well-controlled clinical trials have not indicated a clear superiority of one 2nd generation sulfonylurea over another in improving glycemic control (21). Similarly, 2nd generation sulfonylureas exhibit similar clinical efficacy compared to the 1st generation agents (21). Sulfonylureas do not have
a linear dose-response relationship and the majority of the A1C reduction occurs at half maximum dosage. The effect of sulfonylureas as monotherapy or when added to metformin therapy on A1C levels varies but typically results in reductions in A1C of approximately 0.50-1.5% (8,12,15,22,23). If A1C levels are very high decreases in the range of 1.5-2.0% may be seen (8,15,21). Patients with a short duration of diabetes with residual beta cell function (high C-peptide levels) are likely to be most responsive to sulfonylurea therapy (21). Overtime many patients on sulfonylureas require additional therapies (secondary failure). In the ADOPT study after 5 years, 34% of the patients on glyburide monotherapy had fasting glucose levels > 180 mg/dl (i.e. secondary failure) (24). Similarly, in the United Kingdom Prospective Diabetes Study (UKPDS), only 34% of patients attained an A1c <7 % at 6 years treated with sulfonylureas (glyburide or chlorpropamide) and this number declined to 24 % at 9 years (14). This lack of durability of sulfonylurea therapy is likely to due to beta cell exhaustion. In addition, the weight gain induced by sulfonylurea therapy may also adversely affect glycemic control.

Other Effects

CARDIOVASCULAR DISEASE

The UKPDS studied a large number of newly diagnosed patients with Type 2 diabetes at risk for cardiovascular disease. In this study improved glycemic control with sulfonylureas reduced cardiovascular disease by approximately 16%, which just missed being statistically significant (p=0.052) (25). In the UKPDS, A1c was reduced by approximately 0.9% and the 16% reduction in cardiovascular disease was in the range predicted based on epidemiological studies. Thus, the reduction in cardiovascular events was likely due to improvements in glycemic control and not a direct benefit of sulfonylurea treatment. In support of this conjecture is that in the UKPDS, insulin treatment resulted in a similar decrease in A1c levels and reduction in cardiovascular events (25). Additionally, a large randomized cardiovascular outcome study reported at the 2019 ADA meeting (Carolina Study) found that DPP-4 inhibitor and a SU had similar effects of cardiovascular events.

Side Effects

HYPOGLYCEMIA

The major side effect of sulfonylurea treatment is hypoglycemia, which is more likely to occur and is more severe with long acting sulfonylureas (14,15). In the UKPDS study severe hypoglycemia, defined by need for third-party assistance, occurred each year in 0.4–0.6/100 patients treated with a sulfonylurea while non-severe hypoglycemia was seen in 7.9/100 persons treated with a sulfonylurea (26). Other studies have found even higher rates of severe hypoglycemia with 20–40% of patients receiving sulfonylureas having hypoglycemia and severe hypoglycemia (requiring third-party assistance) occurring in 1–7% of patients (8,26). With continuous glucose monitoring 30% of well controlled patients with Type 2 diabetes had episodes of hypoglycemia that were often asymptomatic and nocturnal (27). Of great concern these hypoglycemic events were associated with EKG changes, particularly QTc prolongation (27). Other studies have also observed a very high rate of hypoglycemia in patients with Type 2 diabetes treated with sulfonylureas when monitored using continuous glucose monitoring (28).

Hypoglycemia typically occurs after periods of fasting or exercise. In light of this hypoglycemic risk, initiation of treatment with sulfonylureas should be at the lowest recommended dose and the dose slowly increased in patients with modestly elevated A1c levels. Older patients (> age 65) and patients with hepatic or renal disease are more likely to experience frequent and severe hypoglycemic reactions (14). Many clinicians avoid the use of long acting sulfonylureas (glyburide) in these high-risk patients as glyburide has a higher risk of hypoglycemia compared to other sulfonylureas (29).

WEIGHT GAIN

In the UKPDS, sulfonylurea treatment caused a net weight gain of approximately 3 kg, which occurred during the first 3–4 years of treatment and then stabilized (15,25). Other studies have similarly observed weight gain with sulfonylurea treatment (21).

CARDIOVASCULAR DISEASE

Based on the University Group Diabetes Project (UGDP) all sulfonylureas carry a “black box”
warning regarding cardiovascular disease. However, there is uncertainty and debate whether sulfonylureas are actually associated with an increased risk of developing cardiovascular disease (14,15,30,31). Unfortunately, the available data does not allow one to reach a firm conclusion. The UKPDS results described above suggest that sulfonylureas do not increase the risk of cardiovascular disease.

FIRST GENERATION SIDE EFFECTS

Chlorpropamide can induce hyponatremia and water retention due to inappropriate secretion of antidiuretic hormone (ADH) (14). In addition, tolbutamide and chlorpropamide, in certain susceptible individuals, is associated with alcohol-induced flushing (14). Because of an increased risk of side effects 1st generation sulfonylureas are seldom used.

RARE SIDE EFFECTS

Intrahepatic cholestasis and allergic skin reactions, including photosensitivity and erythroderma may rarely occur (Package insert).

Contraindications and Drug Interactions

Sulfonylureas are best avoided in patients with a sulfa allergy who experienced prior severe allergic reactions (Package insert). Otherwise cross-reactivity between antibacterial and nonantibacterial sulfonamide agents is rare.

In renal failure, the dose of the sulfonylurea agent will require adjustment based on glucose monitoring to avoid hypoglycemia (14). Because it is metabolized primarily in the liver without the formation of active metabolites, glipizide is the preferred sulfonylurea in patients with renal disease (32).

In the elderly long acting sulfonylureas, such as glyburide, glimepiride and chlorpropamide are not recommended (33).

Sulfonylureas can cause hemolytic anemia in patients with glucose 6-phosphate dehydrogenase (G6PD) deficiency and therefore should be used with caution in such patients (Package insert).

Certain drugs may enhance the glucose-lowering effects of sulfonylureas by inhibition of their hepatic metabolism (antifungals and monoamine oxidase inhibitors), displacing them from binding to plasma proteins (coumarins, NSAIDs, and sulfonamides), or inhibiting their excretion (probenecid) (8).

Summary

While the ability of sulfonylureas to improve glycemic control is robust, the risk of hypoglycemia and weight gain and the uncertainty regarding the effect on cardiovascular disease reduce the desirability of this drug class. In patients at high risk for the occurrence of severe hypoglycemic reactions or in obese patients, using drugs other than sulfonylureas to treat Type 2 diabetes is indicated if possible. Similarly, in patients with atherosclerotic cardiovascular disease or at high risk for cardiovascular disease or renal disease other hypoglycemic drugs have advantages. Nevertheless, because sulfonylureas are generic drugs and very inexpensive, they continue to be widely used and play an important role in the management of patients with Type 2 diabetes.

| Table 8. Summary of the Advantages and Disadvantages of Sulfonylureas |
|---------------------------------------------------------------|------------------|
| **Advantages**                                                 | **Disadvantages** |
| Inexpensive                                                   | Hypoglycemia     |
| Rapid acting                                                  | Weight gain      |
| Once a day administration possible                            | Limited durability|
| Long history of use                                           | Uncertain cardiovascular safety |
|                                                               | Need to titrate dose |
MEGLINATIDES

Introduction

The meglitinides are non-sulfonylurea insulin secretagogues characterized by a very rapid onset and abbreviated duration of action (8,34). Repaglinide (Prandin), a benzoic acid derivative introduced in 1998, was the first member of the meglitinide class. Nateglinide (Starlix) is a derivative of the amino acid D-phenylalanine and was introduced to the market in 2001. Unlike sulfonylureas, repaglinide and nateglinide stimulation of insulin secretion is dependent on the presence of glucose (34,35). As glucose levels decrease, insulin secretion decreases, which reduces the risk of hypoglycemia compared with sulfonylureas.

Meglitinides are rapidly absorbed with maximum serum concentrations generally attained within 1 hour and then quickly metabolized by the liver cytochrome CYP3A4 and CYP2C8 pathways, producing inactive metabolites, resulting in a plasma half-life of around 1 h (8). This rapid onset and short duration of action results in the ability of this class of drugs to predominantly reduce postprandial glucose levels (34). Because of the rapid onset and short duration of action meglitinides are given 1-30 minutes prior to meals. The drug should not be administered if the patient is going to skip the meal.

The pharmacokinetics of meglitinides differ with nateglinide having a faster onset and shorter duration of action than repaglinide (35). Nateglinide stimulates early insulin release faster and to a greater extent than repaglinide with insulin levels returning to baseline levels more rapidly (34,35).

Mechanism of Action

Meglitinides bind to a different site on SUR1 in β cells that is separate from the sulfonylurea binding site (Figure 4) (8,34). The effect of meglitinide binding is similar to the effect of sulfonylureas binding resulting in the closure of the KATP channel leading to cell depolarization and calcium influx resulting in insulin secretion (8,34,35). However, the relatively rapid onset and short duration of action of meglitinides suits their use as prandial glucose-lowering agents (8,34).

Glycemic Efficacy

Studies have shown that A1c reductions are similar to, or slightly less, than those observed with sulfonylurea or metformin treatment when meglitinides are used as monotherapy (8,34). In studies comparing repaglinide monotherapy with sulfonylurea or metformin therapy the decrease in A1c was similar (34,36). In contrast, a study comparing nateglinide with metformin demonstrated that metformin was more effective in lowering A1c levels (37). In a randomized trial comparing repaglinide and nateglinide in patients with type 2 diabetes previously treated with diet and exercise, repaglinide was more effective in lowering A1c levels (1.57% vs. 1.04%) (38). While postprandial glucose levels were similar repaglinide was more effective in reducing fasting glucose levels, probably due to its longer duration of action. These clinical findings are important and can be incorporated into clinical decision making. For example, if the main issue for the patient is postprandial hyperglycemia, and fasting glucose levels are near normal, an agent, such as nateglinide, that has a limited effect on the fasting glucose would be ideal. However, if one needs reductions in both fasting and postprandial glucose levels a longer acting agent such as repaglinide is a better choice.

The recommended starting dose of repaglinide for patients whose A1c is less than 8% is 0.5 mg before each meal (1-30 minutes). For patients whose A1c is 8% or greater the starting dose is 1 or 2 mg orally before each meal. The patient’s dose should be doubled up to 4mg with each meal until satisfactory glycemic control is achieved (should wait one week between increasing dose). The maximum daily dose is 16 mg per day.

Administration

The recommended starting dose of nateglinide is 120 mg three times per day before meals (1-30 minutes). In patients who are near their glycemic goal when treatment is initiated the recommended starting dose of nateglinide is 60 mg three times per day before meals. The maximum dose of nateglinide is 120 mg three times per day before meals.
Other Effects

CARDIOVASCULAR DISEASE

The Navigator study was a double-blind, randomized clinical trial in 9306 individuals with impaired glucose tolerance and either cardiovascular disease or cardiovascular risk factors who received nateglinide (up to 60 mg three times daily) or placebo (39). After 5 years, nateglinide administration did not alter the incidence of cardiovascular outcomes suggesting that meglitinides do not have adverse or beneficial cardiovascular effects.

Side Effects

Similar to sulfonylureas, meglitinides can cause hypoglycemia but the risk of severe hypoglycemia is less (8,34,36). The incidence of hypoglycemia is lower with nateglinide than for repaglinide and nateglinide is less likely to cause severe hypoglycemia (8). In one study, the occurrence of symptomatic hypoglycemia was 2% for nateglinide and 7% for repaglinide (35). Weight gain is also a common side effect of meglitinides (approximately 1-3 kg) with nateglinide leading to less weight gain than repaglinide (8,35).

Contraindications and Drug Interactions

Because meglitinides are metabolized by the liver, these drugs should be used cautiously in patients with impaired liver function (Package insert).

Drugs that inhibit CYP3A4 (for example ketoconazole, itraconazole and erythromycin) or CYP2C8 (for example trimethoprim, gemfibrozil and montelukast) can result in the increased activity of meglitinides enhancing the risk of hypoglycemia and should be avoided if possible (36).

Summary

Meglitinides can be useful drugs when there is a need to specifically lower postprandial glucose levels (i.e. patients with fasting glucose in desired range but elevated post meal glucose levels). Additionally, because of their short duration of action meglitinides can be useful in patients who eat erratically as this class of drugs can be given only before meals and the duration of action will match the postprandial increase in glucose. The risk of severe hypoglycemia and weight gain is less than sulfonylureas but still must be considered in patients treated with meglitinides.

<table>
<thead>
<tr>
<th>Table 9. Summary of the Advantages and Disadvantages of Meglitinides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
</tr>
<tr>
<td>Decrease postprandial glucose</td>
</tr>
<tr>
<td>Flexible dosing</td>
</tr>
<tr>
<td>Relatively inexpensive</td>
</tr>
<tr>
<td>Short action allowing for missing meals</td>
</tr>
</tbody>
</table>

METFORMIN

Introduction

Metformin (Glucophage) is a synthetic analog of the natural product guanidine (8). Since its initial clinical use over 50 years ago, metformin has surpassed the sulfonylureas as the most widely prescribed oral agent for Type 2 diabetes throughout the world because of its proven efficacy on glycemic control as monotherapy and in combination with many other available agents (8). The widespread acceptance of metformin evolved after the realization that lactic acidosis was not a major problem in individuals with normal renal function. Phenformin, a structurally analog of metformin, was previously withdrawn from the market in many countries due its propensity to induce lactic acidosis (8).

Administration

The usual starting dose of metformin is 500 mg twice a day with meals. After 1-2 weeks the dose
can be increased to 1500 mg per day (750 mg twice a day or 500 mg in AM and 1000 mg in PM). After another 1-2 weeks the dose can be increased to 1000 mg twice a day. The slow increase in dosage is to reduce GI side effects and the dose should not be increased if GI side effects are occurring. The maximum dose is 2550 mg per day which can be given as 850 mg three times per day with meals but most patients are treated with 1000 mg twice a day with breakfast and dinner.

The usual starting dose of metformin extended release is 500 mg with the evening meal (largest meal). The dose can be increased by 500 mg weekly depending upon tolerability. The maximum dose is 2000 mg with the evening meal.

Note the dose of metformin may need to be adjusted based on renal function (discussed below).

Metformin should be temporarily discontinued when patients are unable to eat or drink. Metformin is seldom used in hospitalized patients.

Mechanism of Action

Metformin decreases hepatic glucose production and improves hepatic insulin sensitivity but has only a modest impact on peripheral insulin-mediated glucose uptake (i.e. insulin resistance), which is likely due to a reduction in hyperglycemia, triglycerides, and free fatty acid levels (40,41). Hyperinsulinemia is reduced and the decrease in hepatic glucose production results in a decrease in fasting glucose levels (8). In addition, metformin also increases intestinal glucose utilization and stimulates GLP-1 secretion (40,41). Insulin secretion is not increased (8). The cellular and molecular mechanisms that account for these changes are not definitively understood.

LIVER

There are several lines of evidence indicating that the liver plays an important role in metformin’s ability to improve glycemic control (40). In humans and rodents, metformin is concentrated in the liver and blocking the uptake of metformin into the liver in mice prevents the ability of metformin to lower blood glucose levels (40,41). As noted above tracer studies in humans show that metformin lowers hepatic glucose production and increases hepatic insulin sensitivity (40). There are a number of proposed mechanisms by which metformin alters hepatic metabolism (40).

1) Metformin inhibits mitochondrial ATP production by inhibition of Complex I of the respiratory chain and/or inhibiting mitochondrial glycerophosphate dehydrogenase, which is required to carry reducing equivalents from the cytoplasm into the mitochondria for re-oxidation (40,41). The decrease in ATP production could decrease hepatic gluconeogenesis (41). This also leads to an increase in AMP.

2) Metformin increases hepatic AMP levels and AMP is a potent allosteric inhibitor of fructose 1,6-bisphosphatase, a key enzyme in gluconeogenesis (41). In addition, high AMP levels inhibit adenylate cyclase reducing cyclic AMP formation in response to glucagon, which also decreases glycogenolysis and gluconeogenesis (i.e. decreases glucagon activity) (41). The increase in AMP also activates AMP-activated protein kinase.

3) Metformin activates AMP-activated protein kinase, which activates catabolic pathways leading to decreased gluconeogenesis, decreased fatty acid synthesis, and increased fatty acid oxidation (40,41). The changes in fatty acid metabolism are thought to account for the improvement in hepatic insulin sensitivity and the decrease in serum triglyceride levels (40).

INTESTINE

Several lines of evidence indicate that the intestine plays an important role in explaining metformin’s ability to lower blood glucose levels. First, a decrease in hepatic glucose production can only partially account for the decrease in blood glucose (40). Second, in humans with loss-of-function variants in SLC22A1, which decrease the uptake of metformin into the liver, the ability of metformin to lower A1c levels is not impaired (40). Finally, a delayed-release metformin that is retained in the gut, with minimal systemic absorption, is as effective at lowering blood glucose as the standard
metformin formulation in patients with Type 2 diabetes (40,42). There are a number of proposed mechanisms for how the intestine accounts for the beneficial effects of metformin.

1) Metformin increases anaerobic glucose metabolism in the intestine resulting in increased intestinal glucose utilization and decreased glucose uptake into the circulation (40). This is likely due to the inhibition of mitochondrial ATP production described above. The increased utilization of glucose by anaerobic metabolism could contribute to metformin induced weight loss.

2) Metformin increases GLP-1 secretion, which could increase insulin secretion and decrease glucagon secretion (40). The increase in GLP-1 could also contribute to the weight loss or weight neutral effects of metformin.

3) Metformin alters the intestinal microbiome, which could alter glucose metabolism (40,43).

It is clear that there are multiple potential mechanisms by which metformin can improve glucose metabolism and further studies are required to elucidate the relative importance and contribution of these proposed mechanisms and others yet to be identified.

Glycemic Efficacy

Metformin is recommended by the American Diabetes Association and European Association for the Study of Diabetes as the initial therapy in patients with diabetes in conjunction with lifestyle changes (6,7). The typical reduction in A1c with metformin therapy is in the range of 1 to 2.0% (8,44). The decrease in A1c induced by metformin is independent of age, weight and diabetes duration as long as some residual β-cell function remains (8). One retrospective study has reported that African-Americans have a greater decrease in A1c with metformin compared to Caucasians (45). The effect of immediate release and extended release metformin on A1c levels is similar (46). In head-to-head trials, metformin has been shown to produce equivalent reductions in A1c as sulfonylureas and thiazolidinediones but is more potent than DPP-4 inhibitors (44).

The durability of glycemic control with metformin is more prolonged than with sulfonylureas but shorter than with TZDs (24). After 5 years of monotherapy, 15% of individuals on rosiglitazone therapy, 21% of individuals on metformin therapy, and 34% of individuals on glyburide (glibenclamide) therapy had fasting glucose levels above the acceptable range (24). The ability to maintain an A1c <7% was 57 months with rosiglitazone, 45 months with metformin, and 33 months with glyburide (glibenclamide) (24).

In addition to the ability to improve glycemic control in monotherapy, metformin in combination with sulfonylureas, meglinitides, TZDs, DPP-4 inhibitors, SGLT-2 inhibitors, insulin, and GLP-1 receptor agonists lowers A1c levels and often allows for patients to achieve their A1c goals (44). As shown in Table 3 there are a large number of combination tablets that include metformin with other glucose lowering drugs.

Hypoglycemia does not occur with metformin monotherapy (44). Hypoglycemia may occur with metformin during concomitant use with other glucose-lowering agents such as sulfonylureas and insulin.

Other Effects

WEIGHT

Metformin is weight neutral or can sometimes result in a modest weight loss (up to 4 kg) (44). When used in combination with sulfonylureas or insulin it blunts the weight gain induced by these agents.

LIPIDS

Metformin decreases serum triglyceride levels and may modestly decrease LDL cholesterol levels without altering HDL cholesterol levels (47).

CARDIOVASCULAR DISEASE

In the UKPDS, metformin, while producing a similar improvement in glycemic control as insulin or sulfonylureas, markedly reduced cardiovascular disease by approximately 40% (48). In the ten-year follow-up the patients randomized to metformin in
the UKPDS continued to show a reduction in MI and all-cause mortality (49). Two other small randomized controlled trials have also demonstrated cardiovascular benefits with metformin therapy. A study by Kooy et al compared the effect of adding metformin or placebo in overweight or obese patients already on insulin therapy (50). After a mean follow-up of 4.3 years this study observed a reduction in macrovascular events (HR 0.61 CI 0.40-0.94, p=0.02), which was partially accounted for by metformin’s beneficial effects on weight. In this study the difference in A1c between the metformin and placebo group was only 0.3%. Hong et al randomized non-obese patients with coronary artery disease to glipizide vs. metformin therapy for three years (51). A1c levels were similar, but there was a marked reduction in cardiovascular events in the metformin treated group (HR 0.54 CI 0.30-0.90, p=0.026). These results suggest that metformin may reduce cardiovascular disease and that this effect is not due to improving glucose control. Metformin decreases weight or prevents weight gain and lowers lipid levels and these or other non-glucose effects may account for the beneficial effects on cardiovascular disease.

POLYCYSTIC OVARY SYNDROME (PCOS)

In patients with PCOS metformin lowers serum androgen levels, increases ovulations, and improves menstrual frequency (52). Metformin may also be associated with weight loss in some women with PCOS (52). Metformin combined with clomiphene may be the best combination in obese women with PCOS to improve fertility (52). For a detailed discussion of the treatment of PCOS see the chapter on polycystic ovary syndrome in Endotext (52).

CANCER

Multiple epidemiological studies have demonstrated an association between metformin treatment and a reduced cancer incidence and mortality (53,54). Treatment with metformin has been associated with a decreased risk of breast, colon, liver, pancreas, prostate, endometrium and lung cancer and marked reductions in cancer-specific mortality for colon, lung and early-stage prostate cancer and improvements in survival for breast, colon, endometrial, ovarian, liver, lung, prostate and pancreatic cancer (53,54). A wide variety of different mechanisms have been proposed that could account for metformin’s anti-tumor effects providing biological plausibility (54). However, data from large randomized controlled trials have not yet definitively demonstrated whether metformin can prevent the development of cancer or is useful in the treatment of cancer (53,54). Further studies are required to elucidate the potential role of metformin in oncology.

Side Effects

GASTROINTESTINAL

The most common side effects of metformin are diarrhea, nausea, and/or abdominal discomfort, which can occur in up to 50% of patients (8,44). These side effects are usually mild and disappear with continued drug administration. The GI side effects are dose-related and slow titration to allow for tolerance can reduce the occurrence of these symptoms (44). Administering metformin three times a day with meals instead of twice a day may also reduce GI side effects. A small number of patients cannot tolerate the drug, even at low doses (44). Extended-release metformin [metformin XR] causes fewer GI symptoms and can be used in patients who do not tolerate immediate release metformin (44).

LACTIC ACIDOSIS

A very rare complication of metformin therapy is lactic acidosis (44). This complication was much more common with phenformin therapy, the initial biguanide, and the risk with metformin is estimated to be 20 times less (44). The estimated incidence of metformin-associated lactic acidosis is 3–10 per 100,000 person-years (44). This is a potentially lethal complication of metformin therapy that typically occurs when renal dysfunction results in very high blood metformin levels, which inhibit mitochondrial function resulting in the
overproduction of lactate (44). In addition to renal disorders other risk factors for metformin associated lactic acid include sepsis, cardiogenic shock, hepatic impairment, congestive heart failure, and alcoholism (44). In some circumstances the lactic acidosis observed in patients treated with metformin may not be due to metformin but rather to underlying clinical disorders such as severe sepsis.

VITAMIN B12 DEFICIENCY

Studies have demonstrated that vitamin B12 malabsorption is a side effect of metformin therapy (44). A randomized controlled trial showed that metformin 850 mg three times per day for over 4 years resulted in a 19% decrease in B12 levels compared to placebo (56). Moreover, 9.9% of patients treated with metformin developed vitamin B12 deficiency (<150 pmol/l) vs only 2.7% in the placebo group (56). The Diabetes Prevention Program Outcomes Study also demonstrated an increased risk of B12 deficiency with long term metformin use (57). It is now recommended that periodic testing of vitamin B12 levels should be considered in patients on long-term metformin therapy, particularly in the setting of anemia or neuropathy (6).

OVULATION AND PREGNANCY

As discussed above in the polycystic ovary section, treatment of premenopausal women with PCOS with metformin may induce ovulation and thereby result in unplanned pregnancies. In premenopausal anovulatory women started on metformin one needs to discuss the need for contraception.

Contraindications and Drug Interactions

Metformin is contraindicated in patients with advanced kidney or liver disease, acute unstable congestive heart failure, conditions marked by decreased perfusion or hemodynamic instability, major alcohol abuse, or conditions characterized by acidosis (44). Metformin therapy should be suspended during serious illness or surgical procedures. Metformin is seldom used in hospitalized patients.

RENA L DISEASE

A major contraindication to the use of metformin is renal disease (44). Metformin is not metabolized and is excreted intact by the kidneys and therefore kidney function is a major determinant of blood metformin levels. eGFR should be obtained prior to initiating therapy and annually. In patients with renal dysfunction or at risk for developing renal dysfunction eGFR should be obtained more frequently. In patients with a eGFR < 30 mL/min/1.73 m2 metformin therapy is contraindicated (44). In patients with an eGFR between 30-60 mL/min/1.73 m2 metformin can be used but one should consider using lower doses (44). In patients with eGFR < 45 mL/min/1.73 m2 the author typically uses ½ the maximal dose of metformin. In patients with labile renal disease, especially if frequent deteriorations in kidney function occur, metformin is best avoided.

IODINATED CONTRAST STUDIES

FDA guidelines indicate that metformin use should be withheld before iodinated contrast procedures if a) the eGFR is 30–60 mL/min/1.73 m2, b) in the setting of liver disease, alcoholism, or heart failure, or c) if intra-arterial contrast is used. The eGFR should be checked 48 hours later and metformin restarted if renal function remains stable.

DRUG INTERACTIONS

Carbonic anhydrase inhibitors, such as topiramate or acetazolamide, can decrease serum bicarbonate levels and induce a non-anion gap, hyperchloremic metabolic acidosis. Concomitant use of these drugs with metformin may increase the risk for lactic acidosis (Package Insert).

Certain drugs, such as ranolazine, vandetanib, dolutegravir, and cimetidine, may interfere with common renal tubular transport systems that are involved in the renal elimination of metformin and therefore can increase systemic exposure to metformin and may increase the risk for lactic acidosis (Package Insert).

Summary

Metformin is the first line drug for the treatment of diabetes because of excellent efficacy, an outstanding safety profile, low cost, and a long history of use without significant problems.
Table 10. Summary of the Advantages and Disadvantages of Metformin

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inexpensive</td>
<td>GI side effects</td>
</tr>
<tr>
<td>No hypoglycemia</td>
<td>B12 deficiency</td>
</tr>
<tr>
<td>Once a day administration possible</td>
<td>Lactic acidosis (very rare)</td>
</tr>
<tr>
<td>Long history of use</td>
<td>Need to monitor renal function</td>
</tr>
<tr>
<td>No weight gain and maybe weight loss</td>
<td></td>
</tr>
<tr>
<td>May decrease cardiovascular disease</td>
<td></td>
</tr>
</tbody>
</table>

THIAZOLIDINEDIONES (TZDS)

Introduction

Troglitazone (Rezulin), pioglitazone (Actos), and rosiglitazone (Avandia) are members of the thiazolidinedione (TZD) class of insulin sensitizing compounds that activate PPAR gamma (8,58). Troglitazone was withdrawn from the US, European, and Japanese markets in 2000 due to an idiosyncratic hepatic reaction leading to hepatic failure and death in some patients (8,58). This idiosyncratic hepatic reaction has not occurred with pioglitazone or rosiglitazone (58). TZDs decrease insulin resistance and thereby enhance the biological response to endogenously produced insulin, as well as exogenous insulin (58).

Administration

Initiate pioglitazone at 15 mg or 30 mg once a day with or without food. Use 15mg in patients where there is concern of fluid retention. If there is inadequate glycemic control, the dose can be increased in 15 mg increments up to a maximum of 45 mg once daily.

Initiate rosiglitazone at 4 mg once a day with or without food. If there is inadequate glycemic control, the dose can be increased to a maximum of 8 mg once daily.

Because the maximum effect of TZDs on glycemic control may take 10-14 weeks one should wait 12 weeks before deciding whether to increase the dose of TZDs.

Mechanism of Action

The primary effect of pioglitazone and rosiglitazone is the reduction of insulin resistance resulting in an improvement of insulin sensitivity (8,58,59). Pioglitazone and rosiglitazone are selective agonists for the PPAR gamma receptor, a member of the super-family of nuclear hormone receptors that function as ligand-activated transcription factors (58,59). In the absence of ligand, PPARs bind as hetero-dimers with the 9-cis retinoic acid receptor (RXR) and a multi-component co-repressor complex to a specific response element (PPRE) within the promoter region of their target genes (58,59). Once PPAR gamma is activated by ligand, the co-repressor complex dissociates allowing the PPAR-RXR heterodimer to associate with a multi-component co-activator complex resulting in an increased rate of gene transcription (58,59). Additionally, PPAR gamma can repress target gene expression by negative feedback on other signal transduction pathways, such as the nuclear factor kB (NF-kB) signaling pathway, in a DNA binding independent manner (58). The target genes of PPAR gamma include those involved in the regulation of lipid and carbohydrate metabolism and inflammation (58,59).

PPAR gamma is highly expressed in adipose tissue while its expression in skeletal muscle is low (58,59). In the liver PPAR gamma expression is low but increases in obesity and thus in obese individuals it is possible that TZDs directly affect the liver (60). It is likely that the primary effects of TZDs are on adipose tissue, followed by secondary benefits on other target tissues of insulin (58). TZDs promote fatty acid uptake and storage in adipose tissue resulting in a decrease in circulating fatty acids and a decrease in fat accumulation in liver, muscle and pancreas leading to the protection of these tissues from the harmful metabolic effects of higher levels of fatty acids (8,58). This decrease in fat accumulation in liver and muscle leads to an improvement in insulin action and the decrease in the pancreas may improve insulin secretion.
Additionally, PPAR gamma agonists increase the expression and circulating levels of adiponectin, an adipocyte-derived protein with insulin sensitizing activity (58). A decrease in the gene expression of other adipokines involved in induction of insulin resistance, such as TNF-alpha, resistin, etc. are likely to also contribute to the improvement in insulin resistance that occurs with TZDs (58). Finally, the activation of PPAR gamma in other tissues may contribute to the beneficial effects of TZDs.

**Glycemic Efficacy**

Pioglitazone and rosiglitazone decrease A1c levels to a similar degree as metformin and sulfonylurea therapy (typically a 1.0-1.5% decrease in A1c) (8,58). The decreases in fasting plasma glucose were observed as early as the second week of therapy but maximal decreases occurred after 10-14 weeks (8,61). This differs from other hypoglycemic drugs where the maximal effect occurs more rapidly. TZDs lower both fasting and postprandial glucose levels (58). TZDs are more effective in improving glycemic control in patients with marked insulin resistance (62).

TZDs are effective in combination with other hypoglycemic drugs including insulin (8,35,61). TZDs do not cause hypoglycemia when used as monotherapy or in combination with metformin (8,35). In combination with insulin or insulin secretagogues TZDs can potentiate hypoglycemia. If hypoglycemia occurs one needs to adjust the dose of insulin or insulin secretagogues.

The durability of glycemic control with TZDs is more prolonged than with either sulfonylureas or metformin (18). After 5 years of monotherapy, 15% of individuals on rosiglitazone, 21% of individuals on metformin, and 34% of individuals on glyburide (glibenclamide) had fasting glucose levels above the acceptable range (18). The ability to maintain an A1c <7% was 57 months with rosiglitazone, 45 months with metformin, and 33 months with glyburide (glibenclamide) (18). Similar results were observed when pioglitazone therapy was compared to sulfonylurea therapy (63). After 2-years of therapy 47.8% of pioglitazone-treated patients and only 37.0% of sulfonylurea-treated patients maintained an A1c <8%. Studies have shown that TZDs improve and preserve beta cell function, which may account for their better durability (64-66).

**Other Beneficial Effects**

**PROTEINURIA**

A meta-analysis of 15 studies (5 with rosiglitazone and 10 with pioglitazone) involving 2,860 patients demonstrated that TZDs decreased urinary albumin excretion in patients without albuminuria, in patients with microalbuminuria, and in patients with proteinuria (67).

**BLOOD PRESSURE**

TZDs modestly lower BP. In a review of 37 studies TZDs lowered systolic BP by 4.70 mm Hg and diastolic BP by 3.79 mm Hg (68).

**LIPIDS**

The effect of TZDs on lipids depends on which agent is used. Rosiglitazone increases serum LDL cholesterol levels, increases HDL cholesterol levels, and only decreases serum triglycerides if the baseline triglyceride levels are high [66]. In contrast, pioglitazone has less impact on LDL cholesterol levels, but increases HDL cholesterol levels, and decreases serum triglyceride levels (69). It should be noted that reductions in the small dense LDL subfraction and an increase in the large buoyant LDL subfraction are seen with both TZDs (69). Treatment with pioglitazone for 12 weeks resulted in a significant increase in the ability of HDL to facilitate the efflux of cholesterol from cells (70).

In a randomized head to head trial it was shown that pioglitazone decreased serum triglyceride levels and increased serum HDL cholesterol levels to a greater degree than rosiglitazone treatment (71,72). Additionally, pioglitazone increased LDL cholesterol levels less than rosiglitazone. In contrast to the differences in lipid parameters, both rosiglitazone and pioglitazone decreased A1c and C-reactive protein to a similar extent. The mechanism by which pioglitazone induces more favorable changes in lipid levels than rosiglitazone is unclear, but differential actions of ligands for nuclear hormone receptors are well described.
CARDIOVASCULAR DISEASE

Studies with pioglitazone have suggested a beneficial effect on cardiovascular disease. The PROactive study was a randomized controlled trial that examined the effect of pioglitazone vs. placebo over a 3-year period in patients with Type 2 diabetics and pre-existing macrovascular disease (73). With regard to the primary endpoint (a composite of all-cause mortality, non-fatal myocardial infarction including silent MI, stroke, acute coronary syndrome, endovascular or surgical intervention in the coronary or leg arteries, and amputation above the ankle), there was a 10% reduction in events in the pioglitazone group but this difference was not statistically significant (p=0.095). It should be noted that both leg revascularization and leg amputations are not typical primary endpoints in cardiovascular disease trials and these could be affected by pioglitazone induced edema. When one focuses on standard cardiovascular disease endpoints, the pioglitazone treated group did demonstrate a 16% reduction in the main secondary endpoint (composite of all-cause mortality, non-fatal myocardial infarction, and stroke) that was statistically significant (p=0.027). In the pioglitazone treated group, blood pressure, A1c, triglyceride, and HDL cholesterol levels were all improved compared to the placebo group making it very likely that the mechanism by which pioglitazone decreased vascular events was multifactorial.

The IRIS trial was a multicenter, double-blind trial that randomly assigned 3876 patients with insulin resistance but without diabetes and a recent ischemic stroke or TIA to treatment with either pioglitazone or placebo (74). After 4.8 years, the primary outcome of fatal or nonfatal stroke or myocardial infarction occurred in 9.0% of the pioglitazone group and 11.8% of the placebo group (hazard ratio 0.76; P=0.007). All components of the primary outcome were reduced in the pioglitazone treated group. Fasting glucose, fasting triglycerides, and systolic and diastolic blood pressure were lower while HDL cholesterol and LDL cholesterol levels were higher in the pioglitazone group than in the placebo group. Although this study excluded patients with diabetes the results are consistent with and support the results of a protective effect of pioglitazone observed in the PROactive study.

In contrast to the above results, a recent study compared the effect of pioglitazone vs. sulfonylurea on cardiovascular disease and did not observe a reduction in events with pioglitazone treatment (TOSCA.IT) (75). Patients with type 2 diabetes (n=3028), inadequately controlled with metformin monotherapy (2-3 g per day), were randomized to pioglitazone or sulfonylurea and followed for a median of 57 months. Only 11% of the participants had a previous cardiovascular event. The primary outcome was a composite of first occurrence of all-cause death, non-fatal myocardial infarction, non-fatal stroke, or urgent coronary revascularization and occurred in 6.8% of the patients treated with pioglitazone and 7.2% of the patients treated with a sulfonylurea (HR 0.96; NS). Limitations of this study are the small number of events likely due to low risk population studied and the relatively small number of participants. Additionally, 28% of the subjects randomized to pioglitazone prematurely discontinued the medication. Thus, the results of this study should be interpreted with caution.

Further support for the beneficial effects of pioglitazone on atherosclerosis is provided by studies that have examined the effect of pioglitazone on carotid intima-medial thickness. Both the Chicago and Pioneer studies demonstrated favorable effects on carotid intima-medial thickness in patients treated with pioglitazone compared to patients treated with sulfonylureas (76,77). Additionally, in patients with “prediabetes” pioglitazone also slowed the progression of carotid intima-medial thickness (78). Similarly, Periscope, a study that measured atheroma volume by intravascular ultrasonography, also demonstrated less atherosclerosis in the pioglitazone treated group compared to patients treated with sulfonylureas (79).

There are a large number of potential mechanisms by which pioglitazone might reduce cardiovascular disease (Table 11) (66). In addition to altering risk factors pioglitazone has direct anti-atherogenic effects on the arterial wall that could reduce cardiovascular disease (66).
Table 11. Effect of Pioglitazone on Cardiovascular Risk Factors

<table>
<thead>
<tr>
<th>Cardiovascular Risk Factor</th>
<th>Effect of Pioglitazone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visceral Obesity</td>
<td>Decreases</td>
</tr>
<tr>
<td>Hypertension</td>
<td>Lowers BP</td>
</tr>
<tr>
<td>High Triglycerides</td>
<td>Lower TG</td>
</tr>
<tr>
<td>Low HDL cholesterol</td>
<td>Increases HDL cholesterol</td>
</tr>
<tr>
<td>Small dense LDL</td>
<td>Converts small LDL to large LDL</td>
</tr>
<tr>
<td>Endothelial dysfunction</td>
<td>Improves</td>
</tr>
<tr>
<td>Hyperglycemia</td>
<td>Lowers A1c</td>
</tr>
<tr>
<td>Inflammation</td>
<td>Lowers CRP</td>
</tr>
<tr>
<td>PAI-1</td>
<td>Lower PAI-1</td>
</tr>
<tr>
<td>Insulin resistance</td>
<td>Reduces</td>
</tr>
<tr>
<td>Hyperinsulinemia</td>
<td>Lowers insulin levels</td>
</tr>
</tbody>
</table>

While the data from a variety of different types of studies strongly suggests that pioglitazone is anti-atherogenic, the results with rosiglitazone are different. Several meta-analyses of small and short-duration rosiglitazone trials suggested that rosiglitazone was associated with an increased risk of adverse cardiovascular outcomes (80,81). However, the final results of the RECORD study, a randomized trial that was specifically designed to compare the effect of rosiglitazone vs. either metformin or sulfonylurea therapy as a second oral drug in those receiving either metformin or a sulfonylurea on cardiovascular events, have been published and did not reveal a difference in cardiovascular disease death, myocardial infarctions, or stroke (82,83). Similarly, an analysis of patients on rosiglitazone in the BARI 2D trial also did not suggest an increase or decrease in cardiovascular events in the patients treated with rosiglitazone (84).

Thus, while the available data indicate that pioglitazone is anti-atherogenic, the data for rosiglitazone suggests a neutral effect. Whether these differences between pioglitazone and rosiglitazone are accounted for by their differential effects on lipid levels or other factors is unknown.

NONALCOHOLIC FATTY LIVER DISEASE (NAFLD) AND NONALCOHOLIC STEATOHEPATITIS (NASH)

Studies have shown that pioglitazone has beneficial effects on NAFLD and NASH (85). In an early study 55 patients with impaired glucose tolerance or type 2 diabetes and liver biopsy-confirmed NASH were randomized to pioglitazone 45 mg/day or placebo (86). After 6 months of therapy liver enzymes improved and hepatic fat decreased, measured by magnetic resonance spectroscopy. Moreover, histologic findings improved including steatosis (P=0.003), ballooning necrosis (P=0.02), and inflammation (P=0.008). However, fibrosis was unchanged. A more recent study randomized 101 patients with prediabetes or Type 2 diabetes and biopsy-proven NASH to pioglitazone 45 mg/day or placebo for 18 months (87). The primary outcome was a reduction of at least 2 points in the nonalcoholic fatty liver disease activity score in 2 histologic categories without worsening of fibrosis. Pioglitazone treatment resulted in 58% of patients achieving the primary outcome vs. only 17% of the placebo group (p<0.001) and 51% had resolution of NASH compared to 19% of the placebo group (p=0.01). Moreover, pioglitazone treatment improved the fibrosis score.

A recent meta-analysis of 8 randomized controlled trials (5 using pioglitazone and 3 using rosiglitazone) with 516 patients with biopsy-proven NASH reported that TZD treatment was associated with improved advanced fibrosis (OR, 3.15; P = .01), fibrosis of any stage (OR, 1.66; P = .01), and NASH resolution (OR, 3.22; P < .001) (88). Similar results were observed in patients with and without diabetes. Pioglitazone was more effective in improving NASH than rosiglitazone.

These studies demonstrate that pioglitazone has beneficial effects on NAFLD and NASH. Whether this will result in improved clinical outcomes will require additional studies.

POLYCYSTIC OVARY SYNDROME
TZDs by improving insulin sensitivity decrease circulating androgen levels, improve ovulation rates, and improve glucose tolerance in patients with PCOS (52). Small trials have shown some benefit of TZDs for the treatment of infertility, usually in conjunction with clomiphene (52). Concerns regarding toxicity have limited the use of TZDs for the treatment of PCOS but if a patient has diabetes and TZDs are chosen for treating the diabetes one can anticipate beneficial effects on the PCOS.

**Side Effects**

**WEIGHT GAIN**

TZDs lead to an increase in body weight of 2 to 3 kg for every 1 percent decrease in A1c levels (58). In some studies patients gained over 4 kg during a 26-week study (58). Weight gain to a similar degree occurred in monotherapy studies and in studies where TZDs were added to metformin, sulfonylureas, or insulin (58). However, in combination with an SGLT2 inhibitor or a GLP-1 receptor agonist the weight gain was blunted or prevented (89,90). In the ADOPT trial weight gain was greater with TZD therapy than with glyburide therapy (2.5 kg over 5 years) (24). The weight gain induced by TZDs is dose related and can be minimized by using low doses (91).

The TZD induced increase in body weight is due to an expansion of the subcutaneous fat depot whereas the mass of visceral fat remains unchanged or even decreases (58). While weight increases, waist circumference typically remains stable. Stimulation of PPAR gamma in subcutaneous adipocytes stimulates lipid accumulation (59). Fluid retention as discussed below may contribute to the increase in weight.

**FLUID RETENTION**

Edema has been reported in 3.0 to 7.5% of patients treated with the TZDs compared with 1.0 to 2.5% in patients on placebo or treated with other oral antidiabetic therapy (92). The increase in fluid retention is dose related. The risk of developing edema is greatest when a TZD is used in combination with insulin (92). The occurrence of edema is reduced when a TZD is used in combination with an SGLT2 inhibitor (89).

TZD induced edema responds poorly to treatment with thiazide and loop diuretics but responds to diuretics that effect the distal tubules such as spironolactone, triamterene and amiloride (91). Additionally, edema improves when TZD treatment is discontinued (92). The increased fluid retention can lead to an increase in plasma volume resulting in a modest decrease in hemoglobin levels (2-4%) (91).

The increase in fluid retention is likely due to TZDs activating PPAR gamma in the renal tubules leading to the increased expression of the epithelial Na(+) channel resulting in the increased resorption of sodium (93). TZDs have been shown to decrease urine sodium excretion and to increase plasma renin and aldosterone levels (94).

**CONGESTIVE HEART FAILURE (CHF)**

In a meta-analysis of seven studies with a total of 10,040 participants with 641 CHF events, pioglitazone treatment increased the risk of developing CHF by 33% (RR 1.33, 95% CI 1.14–1.54) (95). Another meta-analysis found that pioglitazone was associated with a 51% increased risk of CHF while rosiglitazone was associated with a 173% increase (96). In the RECORD trial, the rosiglitazone group had an increased rate of severe episodes of CHF resulting in hospital admission or death (OR 2.10, 95% CI 1.35 – 3.27, p = 0.001) (82). Similarly, in the PROactive trial, the pioglitazone group also had increased rates of CHF (6% vs. 4%, p = 0.007) (73). Patients treated with TZDs have a higher risk for CHF development if they have a history of cardiovascular disease (91). Interestingly, TZD-associated CHF has not been linked with increased mortality (73,97).

Although TZDs are associated with worsening of CHF or CHF development, they are not associated with adverse effects on cardiac function or structure (91). It is thought that the CHF is mainly due to fluid retention rather than TZDs inducing primarily cardiac dysfunction (91).

**OSTEOPOROSIS**
Large randomized trials have shown that TZDs increase fracture risk, particularly in women. In the ADOPT study, which compared rosiglitazone, metformin, and glyburide, there was no difference in the incidence of fractures in men (98). However, fractures in women at 5 years was increased in the group treated with rosiglitazone (rosiglitazone 15.1%, metformin 7.3%, and glyburide 7.7%) (98). The increase in fractures with rosiglitazone occurred in pre- and postmenopausal women, and were seen predominantly in the lower and upper limbs (98). In the PROActive study there was a higher rate of bone fractures in females treated with pioglitazone vs. placebo (5.1% vs 2.5%) (99). In the RECORD trial upper and distal lower limb fracture rates were increased mainly in women in the rosiglitazone treatment group (82). Hip and femur fracture were not increased with rosiglitazone treatment (82). In the IRIS trial an increased risk of fracture was seen in both males and females (men 9.4% vs 5.2%; HR, 1.83; women 14.9% vs 11.6%; HR, 1.32) (100). In a meta-analysis of 22 randomized controlled trials with 24,544 participants with 896 fracture cases there was a significantly increased incidence of fracture in women (OR=1.94; P<0.001), but not in men (OR=1.02; P=0.83) treated with TZDs (101). The risk of a fracture was similar with rosiglitazone and pioglitazone treatment and appeared to be similar for participants aged <60 years old and older than ≥60 years of age (101). Of note, in the ACCORD trial the risk of fractures in the women treated with rosiglitazone decreased after discontinuing rosiglitazone therapy (102).

In mice, TZDs suppress bone formation and increase bone resorption resulting in decreased bone mass (85). Additionally, TZD administration in mice results in the massive accumulation of adipocytes in the bone marrow cavity (85). In a meta-analysis of 14 trials with 1,734 participants, treatment with TZDs for 3 to 24 months decreased bone mineral density measured by DEXA at the lumbar spine (difference -1.1%; p < 0.0001), total hip (-1.0%; p < 0.0001) and forearm (-0.9%; p = 0.007) (101). In five studies TZD therapy was discontinued and after 24-52 weeks there was no increase in bone mineral density indicating no restoration of bone mineral density with cessation of TZD treatment (101). In an observation study each year of TZD use was associated with greater bone loss at the whole body (additional loss of -0.61% per year), lumbar spine (-1.23% per year), and trochanter (-0.65% per year) in women, but not men (103). The effect of TZD treatment on bone turnover markers varied considerably between individual studies (101). This reduction in bone mass induced by TZD treatment could contribute to the increase in fractures but it is also possible that changes in the microarchitecture of bone also plays a role.

**BLADDER CANCER**

In preclinical studies pioglitazone administration increased bladder cancer in male rats but not in female rats or in mice, dogs, or monkeys (104). In the PROActive study there was a nonsignificant increase in the number of patients who developed bladder cancer (16 vs 6, p = 0.069) (73). In a number of instances, the development of bladder cancer could not plausibly be related to treatment due to the temporal sequence of drug exposure and cancer diagnosis. After eliminating these patients there were six patients with bladder cancer in the pioglitazone group and three patients in the placebo group (73). After 10 years of follow-up, bladder cancer was reported in 0.8% of patients (n = 14) in the pioglitazone versus 1.2% (n = 21) in the placebo group (relative risk 0.65) during the follow-up period (105). In the IRIS study bladder cancer occurred in 12 patients in the pioglitazone group and in 8 in the placebo group (P=0.37) (74). Thus, in large randomized trials the data do not definitively support that pioglitazone significantly increases the risk of bladder cancer. The short duration of the randomized studies and infrequent occurrence of bladder cancer make interpretation of these studies difficult.

Because of the preclinical data the FDA requested that the manufacturer of pioglitazone initiate a prospective study to examine the relationship between pioglitazone and bladder cancer. This 10-year study of 193,099 persons did not find any statistically significant association between pioglitazone treatment and bladder cancer (106). Additionally, in a multinational cohort of 1.01 million patients with Type 2 diabetes there was no evidence for any association between cumulative exposure to pioglitazone and bladder cancer in men or women after adjustment for age, calendar year, diabetes duration, smoking and any ever use of pioglitazone (107). Similarly, no association was observed between rosiglitazone and bladder cancer in men or women (107). In a careful review of 23 epidemiological studies Davidson concluded that there was little evidence that pioglitazone increased the risk of bladder cancer (104).
still warns about the possibility of bladder cancer with pioglitazone use and recommends that pioglitazone not be used in diabetic patients with active bladder cancer or history of bladder cancer (package insert).

MACULA EDEMA

Macular edema has been reported in patients taking TZDs (108,109). Patients may present with blurred vision or decreased visual acuity or be diagnosed on routine ophthalmologic examination. Most patients had peripheral edema at the time macular edema was diagnosed (109). Some patients had improvement in their macular edema after discontinuation of the TZD (109).

OVULATION AND PREGNANCY

As discussed above in the polycystic ovary section, treatment of premenopausal women with PCOS may induce ovulation and thereby result in unplanned pregnancies. In premenopausal anovulatory women started on a TZD one needs to discuss the need for contraception.

### Table 12. The Advantages and Disadvantages of Thiazolidinediones

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Once a day administration</td>
<td>Edema</td>
</tr>
<tr>
<td>Reduces CVD (pioglitazone)</td>
<td>CHF</td>
</tr>
<tr>
<td>Durable Effect</td>
<td>Weight gain</td>
</tr>
<tr>
<td>Reduces NASH</td>
<td>Osteoporosis</td>
</tr>
<tr>
<td>No hypoglycemia</td>
<td>Bladder cancer (pioglitazone)?</td>
</tr>
<tr>
<td>Relatively inexpensive</td>
<td>Macula edema?</td>
</tr>
<tr>
<td>No dose adjustment for renal disease</td>
<td></td>
</tr>
<tr>
<td>Increase HDLc and decrease triglycerides</td>
<td></td>
</tr>
</tbody>
</table>

**CONTRAINdications and Drug Interactions**

TZDs are contraindicated in patients with NYHA Class III or IV heart failure. Pioglitazone should not be used in diabetic patients with active bladder cancer or history of bladder cancer.

Strong CYP2C8 inhibitors (e.g., gemfibrozil) increase pioglitazone and rosiglitazone concentrations and one should limit pioglitazone dose to 15 mg daily (package insert).

**Summary**

TZDs are effective drugs in improving glycemic control and have significant benefits on disorders that occur commonly in patients with Type 2 diabetes (cardiovascular disease, NALFD/NASH, PCOS). Unfortunately, TZDs also have serious side effects, such as CHF, osteoporosis, and weight gain, that limit their use. Clinicians need to balance the advantages and disadvantages of TZDs for the individual patient.

**Alpha-Glucosidase Inhibitors**

**Introduction**

Acarbose (Precose, Glucobay) and miglitol (Glycet) are members of the α-glucosidase inhibitor class of oral anti-hyperglycemic compounds that were introduced in the 1990s (8).

**Administration**

The recommended starting dosage of acarbose and miglitol is 25 mg given orally three times daily at the start of each meal. The dose of acarbose and miglitol can be adjusted at 4 to 8-week intervals based on one-hour postprandial glucose or A1c levels, and on tolerance. The dosage can be increased from 25 mg tid with meals to 50 mg tid with meals. The maximum dose is 100 mg tid with
meals. Note that the dose can be varied based on the amount of carbohydrate in the meal.

**Mechanism of Action**

Alpha-glucosidase inhibitors are competitive, reversible inhibitors of pancreatic α-amylase and membrane-bound intestinal α-glucosidase hydrolase enzymes (8,110). Inhibiting these enzymes prevents the metabolism of disaccharides and oligosaccharides into monosaccharides delaying carbohydrate digestion and absorption (8,110). Carbohydrate absorption occurs more distally in the intestine reducing the postprandial increase in glucose and lowering prandial insulin levels (8,110). Acarbose and miglitol have minimal inhibitory activity against lactase and consequently will not present the increase in plasma glucose following the ingestion of milk or cause lactose intolerance (package insert). In addition to effecting carbohydrate absorption, alpha-glucosidase inhibitors increase postprandial GLP-1 secretion and reduce glucose-dependent insulinotropic polypeptide (GIP) secretion (8).

**Glycemic Efficacy**

The typical decrease in A1c levels is relatively modest with alpha-glucosidase inhibitors (0.5-1.0%) (35,110,111). The decrease in A1c is predominantly due to decreases in post meal glucose levels and alpha-glucosidase inhibitors have only modest effects on fasting glucose levels (8,110,111). Alpha-glucosidase inhibitors can be combined with other hypoglycemic drugs with additive effects and are particularly useful to lower postprandial glucose levels (35,110). Alpha-glucosidase inhibitors are most effective in patients who ingest a high carbohydrate diet and for this reason have been widely used and very effective in Asian populations (8).

These drugs do not cause weight gain and hypoglycemia is uncommon (8,35,111). If a patient experiences hypoglycemia while taking an alpha-glucosidase inhibitor in combination with insulin or sulfonylureas the patient should be instructed to use glucose (gel, tablets, etc.) as alpha-glucosidase inhibitors will prevent the breakdown of sucrose and delay glucose absorption resulting in a failure to quickly correct hypoglycemia. Severe hypoglycemia may require intravenous glucose or intramuscular glucagon administration.

**Other Effects**

**CARDIOVASCULAR DISEASE**

In the STOP-NIDDM trial 1429 subjects with impaired glucose tolerance were randomized to placebo vs. acarbose and followed for 3.3 years (112). In the acarbose group a 49% relative risk reduction in the development of cardiovascular events (hazard ratio 0.51; P =0.03) was observed. Among cardiovascular events, the major reduction was in the risk of myocardial infarction (HR, 0.09; P =0.02). In a smaller trial, 135 patients hospitalized for the acute coronary syndrome who were newly diagnosed with IGT were randomly assigned to acarbose or placebo (113). During a mean follow-up of 2.3 years the risk of recurrent major adverse cardiovascular event was decreased significantly in the acarbose group compared with that in control group (26.7% versus 46.9%, P < 0.05).

Despite these favorable observations a large recently published trial failed to demonstrate a beneficial effect of acarbose in Chinese patients with impaired glucose tolerance (ACE trial) (114). In a randomized trial acarbose vs. placebo was compared in 6522 patients with coronary heart disease and impaired glucose tolerance. The primary outcome was cardiovascular death, non-fatal myocardial infarction, non-fatal stroke, hospital admission for unstable angina, and hospital admission for heart failure and patients were followed up for a median of 5 years. The primary outcome was similar in the acarbose and placebo groups (hazard ratio 0.98; p=0.73). No significant differences were seen for death from any cause, cardiovascular death, fatal or non-fatal myocardial infarction, fatal or non-fatal stroke, hospital admission for unstable angina, hospital admission for heart failure, or impaired renal function.

Thus, whether acarbose favorably affects cardiovascular disease in patients at high risk for developing diabetes is uncertain. Moreover, the effect of acarbose on cardiovascular disease in patients with diabetes is unknown.

**Side Effects**

Gastrointestinal side effects of alpha-glucosidase inhibitors include flatulence, abdominal discomfort,
and diarrhea and are very commonly encountered (8,35,111). These side effects can lead to the inability to tolerate these drugs. A high carbohydrate diet may worsen the GI adverse effects. Over time the GI symptoms tend to decrease as the intestines adapt (110). GI side effects are due to the mechanism of action of alpha-glucosidase inhibitors (110). The inhibition of carbohydrate digestion in the small intestine leads to the delivery of undigested carbohydrates to the large intestine where microorganisms metabolize them into short-chain fatty acids, methane, carbon dioxide, and hydrogen, that can cause abdominal discomfort, increased flatulence, and diarrhea (110).

Acarbose, particularly at doses in excess of 50 mg tid, may give rise to elevations of serum transaminases and, in rare instances, hyperbilirubinemia. It is recommended that serum transaminase levels be checked every 3 months during the first year of treatment with acarbose and periodically thereafter. If elevated transaminases are observed, a reduction in dosage or withdrawal of therapy may be indicated, particularly if the elevations persist (package insert).

Contraindications and Drug Interactions

Acarbose and miglitol are contraindicated in patients with inflammatory bowel disease, colonic ulceration, intestinal obstruction or those predisposed to intestinal obstruction, patients with chronic intestinal disease, or conditions that will be worsened by the increased gas formation in the intestine (35) (package insert). Acarbose is contraindicated in patients with cirrhosis (package insert).

Acarbose and miglitol should not be used in patients with a creatinine > 2 mg/dl (package insert).

Summary

Alpha-glucosidase inhibitors are excellent drugs for lowering postprandial glucose levels. Unfortunately, because of their GI side effects many patients are unable to tolerate these drugs. Additionally, the need for three times a day administration makes it difficult for patients to comply with these drugs.

<table>
<thead>
<tr>
<th>Table 13. Advantages and Disadvantages of Alpha-Glucosidase Inhibitors</th>
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<td>Weight neutral</td>
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<td>Decreases postprandial glucose</td>
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**SODIUM-GLUCOSE TRANSPORT PROTEIN 2 (SGLT2) INHIBITORS**

Introduction

There are currently four SGLT2 inhibitors available (Canagliflozin/Invokana; Dapagliflozin/Farxiga; Empagliflozin/Jardiance; Ertugliflozin/Stelzatro) (115). These drugs are very similar and there are only a few differences between these agents.

Administration

The recommended starting dose of canagliflozin is 100 mg once daily who have an eGFR of 60 mL/min/1.73 m² or greater and require additional glycemic control, the dose can be increased to 300 mg once daily.

The recommended starting dose of dapagliflozin is 5 mg once daily, taken in the morning, with or without food. In patients tolerating dapagliflozin 5 mg once daily who require additional glycemic control, the dose can be increased to 10 mg once daily.

The recommended starting dose of empagliflozin is 10 mg once daily in the morning, taken with or without food. In patients tolerating empagliflozin, the dose may be increased to 25 mg.
The recommended starting dose of ertugliflozin is 5 mg once daily, taken in the morning, with or without food. In patients tolerating ertugliflozin 5 mg once daily who require additional glycemic control, the dose can be increased to 15 mg once daily.

Before initiating SGLT2 inhibitor therapy one should assess renal function and volume status.

**Mechanism of Action**

SGLT2 is a low-affinity, high-capacity glucose transporter in the proximal tubules of the kidneys, which is responsible for the reabsorption of the majority of the filtered glucose (approximately 90%) entering the tubules (8,116). SGLT1, which is predominantly expressed in the intestines is also expressed in the kidneys, is a high-affinity, low-capacity glucose transporter in the proximal tubules, which makes a minor contribution to the reabsorption of filtered glucose (approximately 10%) (8,116). These active transporters in conjunction with Glut 1 and 2 transporters are capable of reabsorbing virtually all the filtered glucose when blood glucose levels are less than approximately 180mg/dL. When blood glucose levels are greater than approximately 180mg/dL, glucose begins to appear in the urine (i.e. glycosuria). The higher the blood glucose level the greater the quantity of glucose in the urine. Patients with Type 2 diabetes express a higher number of SGLT2 transporters in the proximal tubule than do healthy individuals and hence glucose reabsorption from the glomerular filtrate is increased in patients with diabetes and glycosuria occurs at a higher blood glucose level (typically approximately 220mg/dl (117).

Inhibition of SGLT2 by drugs results in glycosuria and can lead to the excretion of 60–90 grams of glucose in the urine per day (Figure 5) (8). The amount of glucose excreted in the urine can vary considerably depending on renal function and the degree of hyperglycemia (8). Decreased renal function results in a decrease in filtered glucose and less glucose in the urine while high blood glucose levels increase filtered glucose and increases the loss of glucose in the urine (8). The ability of the inhibition of SGLT2 to lower blood glucose levels is not dependent on insulin action and hence is not affected by insulin levels or insulin resistance (8). As will be discussed below many of the non-glucose lowering benefits and side effects of SGLT2 inhibitors can be explained by the increase in glucose excretion in the urine. It should be recognized that glycosuria results in an osmotic diuresis. Additionally, because the SGLT2 transporters also facilitate the reabsorption of sodium from the filtrate there is also the loss of sodium in the urine.
Glycemic Efficacy

A meta-analysis of 66 randomized trials found that SGLT2 inhibitors decreased A1c levels by 0.4 to 1.1% (118). In comparison to other hypoglycemic drugs it was found that SGLT-2 inhibitors showed a greater efficacy than DPP-4 inhibitors and similar or slightly less efficacy compared to metformin and TZDs (12,118). Sulfonylureas appeared to be superior to SGLT-2 inhibitors at 12 weeks, but at 24- and 52-weeks efficacy was similar or slightly lower (12,118). However, SGLT-2 inhibitors produced a greater reduction in HbA1c than sulfonylureas at 104 weeks perhaps due to the lack of durability of sulfonylurea therapy discussed earlier (118). The A1c lowering ability of the different SGLT2 inhibitors is similar but A1c is reduced to a slightly greater extent by high-dose canagliflozin, which is probably a result of its additional action of inhibiting SGLT1 in the intestine decreasing dietary glucose absorption (115,116,118). SGLT2 inhibitors when used as an add-on therapy to metformin, insulin, thiazolidinediones, DPP-4 inhibitors, GLP-1 receptor agonists, sulfonylureas, or metformin ± DPP-4 inhibitor were similarly effective in reducing A1c levels as when used in monotherapy (8,116). The efficacy of SGLT2 inhibitors is dependent on renal function and as renal function decreases the ability of these drugs to lower A1c levels diminishes (8,116). SGLT2 inhibitors lower both fasting and postprandial glucose levels (116). In monotherapy SGLT2 inhibitors have a low risk of causing hypoglycemia but in combinations with insulin or sulfonylureas may potentiate the development of hypoglycemia (8). In patients in good glycemic control one often decreases the insulin or sulfonylurea dose when initiating therapy with an SGLT2 inhibitor.

Other Effects

WEIGHT

SGLT2 inhibitors lead to weight loss (8,116). In general patient’s lose approximately 1- 3 kg on these drugs (8,115,116). SGLT2 inhibitor-induced weight loss results primarily from a decrease in fat mass, including reductions in visceral and subcutaneous adipose tissue (116). The weight loss is due to the loss of glucose in the urine, which
represents the loss of calories (116,119). The excretion of 50 grams of glucose in the urine is equivalent to the loss of 225 calories (50-grams X 4.5 calories per gram of glucose). However, the amount of glucose lost in the urine should result in a greater weight loss than is typically observed and a compensatory increase in food intake blunts the weight loss (119). There are likely to be other homeostatic mechanisms that also play a role in limiting weight loss with SGLT2 inhibitors.

BLOOD PRESSURE

SGLT2 inhibitors decrease systolic BP by approximately 3-6 mmHg and diastolic BP by approximately 2-3 mmHG (8,116). Patients with poorly controlled BP at baseline experience the largest reduction in BP (115). SGLT2 inhibitors lower BP by promoting an osmotic diuresis and decreasing intravascular volume (116). Weight loss may also contribute to the decrease in BP.

LIPID LEVELS

SGLT2 inhibitors cause a small increase in LDL and HDL cholesterol levels. In the EMPA-REG outcome study, described in detail below, LDL cholesterol levels were increased by 2-4 mg/dL and HDL cholesterol by 2-3 mg/dL in the group treated with empagliflozin (120). Similarly, in the CANVAS outcome study, discussed in detail below, LDL cholesterol and HDL cholesterol were also marginally increased in the canagliflozin treated group (LDL cholesterol 4-5 mg/dL and HDL cholesterol 2-3 mg/dL) (121). In a meta-analysis of 43 randomized trials with 22,528 patient’s triglyceride levels were decreased by 2 mg/dL (122). It is unlikely that these small changes in LDL and HDL cholesterol and triglycerides are of clinical significance. The mechanism for these increases in LDL and HDL cholesterol is unknown but could be due to a decrease in plasma volume. The decrease in triglycerides might be secondary to weight loss.

URIC ACID

SGLT2 inhibitors lower blood uric acid levels (123). This decrease is due to an increase in uric acid excretion by the kidneys.

CARDIOVASCULAR

There have been four large randomized studies of the effect of SGLT2 inhibitors on cardiovascular events published (others are in progress).

EMPA-REG Outcome Trial

In this study, 7020 patients with established cardiovascular disease were randomly assigned to receive 10 mg or 25 mg of empagliflozin or placebo once daily and were followed for 3.1 years (120). In the combined empagliflozin treated groups there was a statistically significant 14% reduction in the primary outcome (death from cardiovascular causes, nonfatal myocardial infarction, or nonfatal stroke). As compared with placebo, empagliflozin treatment did not result in a significant difference in the occurrence of non-fatal myocardial infarction or strokes. However, empagliflozin resulted in a significantly lower risk of death from cardiovascular causes (hazard ratio, 0.62), death from any cause (hazard ratio, 0.68), and hospitalization for heart failure (hazard ratio, 0.65). The beneficial effects of empagliflozin were noted to occur very rapidly and the beneficial effects on heart failure appeared to be the dominant effect compared to effects on atherosclerotic events. Decreases in cardiovascular outcomes and mortality with empagliflozin occurred across the range of cardiovascular risk (124). Additionally, the reduction in hospitalizations for heart failure and cardiovascular death were observed both in patients with and without heart failure at baseline (125).

CANVAS Trial

The effects of placebo vs. canagliflozin 100mg or 300mg per day were determined in two combined trials involving a total of 10,142 participants with type 2 diabetes and high cardiovascular risk (approximately 70% of patients had established cardiovascular disease) (121). The primary outcome was a composite of death from cardiovascular causes, nonfatal myocardial infarction, or nonfatal stroke and the mean follow-up was 188 weeks. The primary outcome was reduced in the canagliflozin group (hazard ratio, 0.86; P=0.02). Death from any cause (hazard ratio 0.87; 95% CI 0.74-1.01) and death from cardiovascular disease (hazard ratio 0.87; 95% CI 0.72-1.06) were reduced but were not statistically significant. Similarly, canagliflozin treatment did not result in a significant difference in non-fatal strokes
or non-fatal myocardial infarctions (hazard ratio 0.90 for stroke and 0.85 for myocardial infarction). As seen with empagliflozin, hospitalization for heart failure was markedly reduced (hazard ratio 0.67; 95% CI 0.52-0.87) and this beneficial effect occurred rapidly.

**CREDENCE Trial**

In a second canagliflozin trial that focused on kidney disease, a decrease in cardiovascular events was also observed (126). In this double-blind trial 4401 patients with chronic kidney disease were randomized to canagliflozin 100mg per day or placebo and followed for a median of 2.62 years. All the patients had an eGFR of 30 to <90 ml per minute per 1.73 m² and albuminuria (ratio of albumin [mg] to creatinine [g], >300 to 5000). In this trial hospitalization for heart failure was reduced by 39%.

**DECLARE–TIMI 58 Trial**

The effect of a 3rd SGLT2 inhibitor on cardiovascular events has been reported (127). 17,160 patients, including 10,186 without atherosclerotic cardiovascular disease, were randomized to dapagliflozin 10mg per day or placebo and followed for a median of 4.2 years. The primary outcome was a composite of major adverse cardiovascular death, myocardial infarction, or ischemic stroke. The primary efficacy outcomes were MACE and a composite of cardiovascular death or hospitalization for heart failure. Dapagliflozin did not result in a lower rate of major adverse cardiovascular events (8.8% in the dapagliflozin group and 9.4% in the placebo group; hazard ratio, 0.93; P=0.17) but did result in a lower rate of cardiovascular death or hospitalization for heart failure (4.9% vs. 5.8%; hazard ratio, 0.83; P=0.005), which reflected a lower rate of hospitalization for heart failure (hazard ratio, 0.73; 95% CI, 0.61 to 0.88). Interestingly, in the patients with a history of a previous MI dapagliflozin reduced the risk of a major cardiovascular event (HR 0.84; P=0.039), whereas there was no effect in patients without previous MI (128). Dapagliflozin reduced the risk of heart failure in patients with and without a history of heart failure but the benefit was greater in patients with a history of heart failure (with heart failure HR 0.62; 95% CI, 0.45-0.86; without heart failure HR 0.88; 95% CI, 0.74-1.03) (129).

**Summary**

Thus, four SGLT2 inhibitor clinical trials demonstrated a decrease in heart failure with SGLT2 inhibitor therapy. In a meta-analysis of three of these trials (CASCADE was not included) it was observed that SGLT2 inhibitors reduced the risk of cardiovascular death or hospitalization for heart failure by 23% (p<0.0001), with a similar benefit in patients with and without atherosclerotic cardiovascular disease and with and without a history of heart failure (130). Additionally, greater reductions in hospitalizations for heart failure was observed in patients with more severe kidney disease at baseline (130).

The mechanisms accounting for the beneficial effects of SGLT2 inhibitors on heart failure are uncertain (131). Glycemic control was better in the SGLT2 inhibitor treated patients but it is doubtful that this could account for the observed results. SGLT2 inhibitor treatment was associated with small reductions in weight, waist circumference, uric acid level, and systolic and diastolic blood pressure, with no increase in heart rate and small increases in both LDL and HDL cholesterol. Whether these changes played a role in reducing events remains to be determined. It is possible that hemodynamic changes secondary to the osmotic diuresis induced by SGLT2 inhibitors contributed to the beneficial effects. In an analysis of the EMPA-REG OUTCOME trial, the change in hematocrit (~3% increase), corresponding to ~7% reduction in plasma volume, accounted for approximately 50% of the benefit of the drug on cardiovascular death (132). Additionally, SGLT2 inhibitors increase glucagon secretion, which promotes the production of ketone bodies such as beta-hydroxybutyrate that are utilized by the heart for energy production. It is possible that this alternative source of energy could be protective for heart function. Finally, there may be direct effects of SGLT2 inhibition on myocardial and renal metabolism (131,133,134). Further studies are required to better elucidate the mechanism of the beneficial effects of SGLT2 inhibitors on heart failure.

**RENAL DISEASE**

The large randomized SGLT2 inhibitor cardiovascular outcome trials described above also
examined the effect of these drugs on renal disease.

**EMPA-REG Outcome Trial**

The effect of empagliflozin on renal outcomes was studied in 4124 patients with Type 2 diabetes who were randomized to empagliflozin (10 mg or 25 mg) or placebo (135). The prespecified outcomes were progression to macroalbuminuria, doubling of the serum creatinine level, initiation of renal-replacement therapy, or death from renal disease and incident albuminuria. Worsening nephropathy occurred in 12.7% of patients in the empagliflozin group and in 18.8% of patients in the placebo group, a relative risk reduction of 39% (P<0.001). Progression to macroalbuminuria was reduced 38%, doubling of serum creatinine by 44%, and initiation of renal replacement therapy by 55% (all statistically significant). The renal benefit was seen regardless of baseline eGFR, occurring in individuals with an eGFR as low as 30 mL/min/1.73 m². While empagliflozin caused an initial decrease in eGFR over the long term eGFR decreased in the placebo group at a more rapid rate than the empagliflozin group. Additionally, patients treated with empagliflozin were more likely to convert from microalbuminuria to normoalbuminuria (hazard ratio [HR] 1.43; p=0.0001) or from macroalbuminuria to microalbuminuria or normoalbuminuria (HR 1.82; p<0.0001), and were less likely to experience a sustained deterioration from normoalbuminuria to microalbuminuria or macroalbuminuria (HR 0.84; p=0.0077) (136).

**CANVAS Trial**

Similar to the results seen with empagliflozin, canagliflozin has also been shown to decrease renal disease. 10,142 participants with Type 2 diabetes and high cardiovascular risk were randomly assigned to receive canagliflozin or placebo and were followed for a mean of 188.2 weeks (121). Progression of albuminuria occurred less frequently in the canagliflozin group (hazard ratio of 0.73; 95% CI, 0.67 to 0.79). In addition, regression of albuminuria also occurred more frequently in the canagliflozin group (hazard ratio, 1.70; 95% CI, 1.51 to 1.91). Most importantly, the composite outcome of sustained 40% reduction in eGFR, the need for renal-replacement therapy, or death from renal causes occurred less frequently in the canagliflozin group (hazard ratio of 0.60; 95% CI, 0.47 to 0.77). Annual eGFR decline was slower (slope difference between groups 1.2 mL/min/1.73 m² per year, 95% CI 1.0-1.4) and mean urinary albumin creatinine ratio was 18% lower (95% CI 16-20) in participants treated with canagliflozin than in those treated with placebo (137). The benefits of canagliflozin on renal disease occurred across a wide spectrum of eGFR ranging from 30-45 to ≥90 mL/min/1.73 m² (138).

**CREDENCE Trial**

The CREDENCE Trial focused on renal disease. In a double-blind trial 4401 patients with chronic kidney disease were randomized to canagliflozin or placebo and followed for a median of 2.62 years (126). All the patients had an eGFR of 30 to <90 mL/min/1.73 m² and albuminuria (ratio of albumin [mg] to creatinine [g], >300 to 5000) and were treated with renin-angiotensin system blockade. The primary outcome was a composite of end-stage kidney disease (dialysis, transplantation, or a sustained estimated GFR of <15 mL/min/1.73 m²), a doubling of the serum creatinine level, or death from renal or cardiovascular causes. The primary outcome was 30% lower in the canagliflozin group (hazard ratio, 0.70; P = 0.00001). The relative risk of the renal-specific composite of end-stage kidney disease, a doubling of the creatinine level, or death from renal causes was 34% lower (hazard ratio, 0.66; P<0.001), and the relative risk of end-stage kidney disease was 32% lower (hazard ratio, 0.68; P = 0.002). Benefits were seen regardless of baseline eGFR.

**DECLARE–TIMI 58 Trial**

In this trial of 17,160 participants a secondary outcome was a renal composite outcome defined as a sustained decrease of 40% or more in eGFR to less than 60 mL/min/1.73 m², new end-stage renal disease, or death from renal or cardiovascular causes (127). As seen in the other SGLT2 inhibitor studies there was a decrease in the development of renal disease with the incidence of the renal outcome 4.3% in the dapagliflozin group vs. 5.6% in the placebo group (hazard ratio, 0.76; 95% CI, 0.67 to 0.87). Excluding death from cardiovascular causes as part of the composite endpoint, the reduction in renal events was even more impressive (HR 0.53 p<0.0001) (139). The risk of end-stage renal disease or renal death was lower...
in the dapagliflozin group than in the placebo group (HR 0.41; p=0.012) (139).

**Summary**

These four trials clearly demonstrate that SGLT2 inhibitors have beneficial effects on renal function and decrease the development of renal disease. In a meta-analysis of three of these trials (CASCADE was not included) it was observed that SGLT2 inhibitors were renoprotective and reduced the composite of worsening of renal function, end-stage renal disease, or renal death by 45% (130). This renal disease benefit was seen in patients with and without atherosclerosis (130). The reduction in the composite renal endpoint was present across all baseline eGFR levels but was greatest in those with good renal function at baseline (33% reduction in patients with an eGFR less than 60 mL/min/1.73 m², 44% reduction in patients with an eGFR between 60 and 90 mL/min/1.73 m², and 56% reduction in patients with an eGFR > 90 mL/min/1.73 m²) (130). These renal benefits are independent of improvement in glycemic control (140).

The mechanism accounting for this effect is unknown but a leading hypothesis is that an increase of sodium chloride in the macula densa due to SGLT2 inhibition triggers a cascade that reduces GFR through constriction of the afferent glomerular arterioles (tubuloglomerular feedback) (116,140). This would reduce glomerular hydrostatic pressure and initially decrease GFR, an effect that is observed with SGLT2 treatment, but in the long run this decrease in GFR protects the kidney from damage resulting in improved kidney function long-term (116).

**NONALCOHOLIC FATTY LIVER DISEASE (NAFLD) AND NONALCOHOLIC STEATOHEPATITIS (NASH)**

Numerous studies have shown that treatment with SGLT-2 inhibitors decrease liver enzymes (85,141-145). Moreover, studies have shown a decrease in liver fat and liver stiffness (85,141,142,144,145). A study of 5 patients showed an improvement in liver histology after 24 weeks of therapy with canagliflozin (146). Further studies are required to determine whether SGLT-2 inhibitors will result in clinical benefits in patients with NAFLD and NASH.

**Side Effects**

**URINARY TRACT INFECTIONS**

In some but not all studies an increased risk of urinary tract infections was observed with SGLT2 inhibitors (8,115). In the large randomized cardiovascular outcome trials, an increase in urinary tract infections were not observed (120,121,127). In a large meta-analysis of 86 randomized trials with 50,880 patients an increase in urinary tract infections was also not observed (147). The potential increase in the occurrence and severity of urinary tract infections is due to the glycosuria as glucose is an excellent substrate for the growth of microorganisms.

**GENITAL MYCOTIC INFECTIONS**

Genital mycotic infections (mainly balanitis and vulvovaginitis) are increased with SGLT2 inhibitor treatment (115). The risk of genital mycotic infections is greater in women than men. In a meta-analysis that included over 2000 patients treated with canagliflozin 100 mg or 300 mg vs. placebo, genital mycotic infections were seen in greater than 10% of women (100mg-10.4%, 300 mg-11.4%, placebo-3.2%) and around 4% of men (100 mg-4.2%, 300 mg-3.7%, placebo-0.6%) (148). In uncircumcised men the risk of genital mycotic infections is greater than in circumcised men. Genital mycotic infections are the most common side effect seen with SGLT2 inhibitors but fortunately these infections are generally mild and relatively easy to treat (8).

The increase in genital mycotic infections is due to the glycosuria as glucose is an excellent substrate for the growth of Candida.

**FOURNIER GANGRENE**

Fournier gangrene (FG) is a necrotizing fasciitis of the perineum that is characterized by a rapidly progressive necrotizing infection of the external genitalia, perineum, and perianal region (149). Many of the patients with FG have diabetes (32-66%) (149). FG occurs most commonly in males and is a rare condition with an incidence of 3.3 in 100,000 men aged 50 to 79 years (149). In a recent case series of 59 patients over a 10-year period at a single institution, the incidence was estimated at
32 cases per 100,000 admissions (150). Risk factors included very high A1c (mean 9.6%), obesity, immunocompromised state, and illicit drug use (150). FG is a urologic emergency and requires treatment with broad-spectrum antibiotics and immediate surgical intervention (149).

A recent report described 55 FG cases in patients treated with SGLT2 inhibitors in the last 6 years since they were approved for use in the US (149). In contrast, only 19 cases of FG were reported in 35 years among patients receiving other hypoglycemic drugs. All of the SGLT2 inhibitors were associated with FG except ertugliflozin, which is likely explained by this drug only recently being approved for the treatment of diabetes. However, the authors were unable to assess the incidence of FG or whether SGLT2 inhibitors were causative.

Early recognition of FG is essential to reduce morbidity and mortality. Typical presentations include systemic symptoms, such as fatigue, fever, and malaise, and local symptoms that include tenderness, erythema, and swelling (149). Pain out of proportion to the clinical findings is highly suggestive of necrotizing fasciitis (149).

HYPOVOLEMIA AND HYPOTENSION

SGLT2 inhibitors induce an osmotic diuresis (115). This effect can result in postural dizziness, orthostatic hypotension, falls, and dehydration, particularly in elderly individuals, patients with kidney disease, patients on either diuretics or medications that interfere with the renin-angiotensin-aldosterone system (e.g., angiotensin-converting-enzyme inhibitors, angiotensin receptor blockers), and patients with low systolic blood pressure (115) (package insert). Volume status should be determined prior to initiating therapy with an SGLT2 inhibitor.

ACUTE KIDNEY INJURY

SGLT2 inhibitors have been reported to cause acute kidney injury (115). It is likely that volume depletion and hypotension lead to the acute kidney injury (115). In an analysis of two large health care utilization cohorts SGLT2 inhibitors were not associated with an increased risk of acute kidney injury (151). Similarly, in the cardiovascular outcome studies described earlier an increase in acute kidney injury was not observed.

Before initiating SGLT2 inhibitor therapy one should consider factors that may predispose patients to acute kidney injury including hypovolemia, chronic renal insufficiency, congestive heart failure, and concomitant medications (diuretics, ACE inhibitors, ARBs, NSAIDs). Consider temporarily discontinuing SGLT2 inhibitors in any setting of reduced oral intake (such as acute illness or fasting) or fluid losses (such as gastrointestinal illness or excessive heat exposure) (package insert).

DIABETIC KETOACIDOSIS

Diabetic ketoacidosis (DKA) has been observed in patients treated with SGLT2 inhibitors but is a rare side effect (6,115). In some instances, the glucose levels are not very elevated despite the patient having DKA (euglycemic DKA) and this can result in a delay in diagnosing DKA (115). The prevalence of DKA in 17,596 patients from randomized studies of canagliflozin was very low (100 mg-0.07%, 300 mg-0.11%, and placebo-0.03%) (152). SGLT2 inhibitors were associated with approximately twice the risk of diabetic ketoacidosis compared to treatment with DPP-4 inhibitors (153). Many of the DKA events occurred in patients with Type 2 diabetes treated with insulin who had reduced or stopped insulin or experienced an intercurrent illness that could precipitate DKA (8,154). In some instances the patients were thought to have Type 2 diabetes but actually had latent autoimmune diabetes of adults (LADA), a form of Type 1 diabetes (8). The hyperglycemia in DKA associated with SGLT2 inhibitors is typically mild because the SGLT2 inhibitors reduce blood glucose levels (8). SGLT2 inhibitors should be temporarily discontinued in clinical situations known to predispose to ketoacidosis (e.g., prolonged fasting due to acute illness or surgery) (package insert). Patients should be educated regarding this potential complication and in high risk patients (for example patients on insulin therapy) one could provide the patient with ketone test strips to facilitate the early diagnosis of DKA.

A possible mechanism for the increased risk of DKA is SGLT2 inhibitors increasing plasma glucagon levels thereby increasing ketone production (115,154). In combination with the low insulin levels this could potentiate the development of DKA.

OSTEOPOROSIS AND FRACTURES
In the CANVAS cardiovascular outcome study, the rate of all fractures was higher in the canagliflozin group than in the placebo group (15.4 vs. 11.9 participants with fracture per 1000 patient-years; hazard ratio, 1.26; 95% CI, 1.04 to 1.52) (121). A similar trend was observed for low-trauma fracture events (canagliflozin 11.6 vs. placebo 9.2 participants with fracture per 1000 patient-years; hazard ratio, 1.23; 95% CI, 0.99 to 1.52) (121). The incidence of fractures in the CANVAS study was increased with canagliflozin vs. placebo across subgroups based on sex, age, duration of Type 2 diabetes, baseline eGFR, and prior fracture history (155). Notably, the increase in fractures associated with canagliflozin treatment began within weeks of drug initiation indicating that the increased risk occurs rapidly (155).

In contrast, both the EMPA-REG and DECLARE cardiovascular outcome studies did not demonstrate an increase in fractures with empagliflozin or dapagliflozin, respectively (120,127). Additionally, in the CREDENCE outcome study, canagliflozin did not increase fracture risk in patients with chronic kidney disease defined as an eGFR of 30 to <90 mL/min/1.73 m2 and albuminuria (ratio of albumin [mg] to creatinine [g], >300 to 5000) (126). Similarly, in a pooled analysis of 8 randomized canagliflozin studies with 5867 participants (CANVAS trial excluded) an increase in fractures was not observed (155). Moreover, in a meta-analysis of 27 randomized controlled trials with an average duration of 64 weeks that compared the efficacy and safety of SGLT2 inhibitors to a placebo in 20,895 participants there was no increased risk of fractures with SGLT2 inhibitor treatment (RR 1.02; 95% CI 0.81-1.28) (156).

Several studies have examined the effect of SGLT2 inhibitors on bone mineral density. Canagliflozin was associated with a decrease in total hip bone mineral density over 104 weeks, (placebo-subtracted changes:100mg -0.9% and 300mg -1.2%), but did not result in changes in bone mineral density in the femoral neck, lumbar spine, or distal forearm (157). In a 2-year study dapagliflozin did not significantly affect bone mineral density at the lumbar spine, femoral neck, or total hip (158). In a 26-week study ertugliflozin also had no adverse effect on bone mineral density (159). Thus, the evidence that SGLT2 inhibitors increase the risk of osteoporosis and fractures, with the possible exception of canagliflozin, is not very strong. One should recognize though, that the hypovolemia and hypotension could increase the risk of falls and thereby increase the risk of fractures in susceptible individuals.

**AMPUTATIONS**

In the CANVAS study described above, canagliflozin was associated with an increased risk of amputations (hazard ratio, 1.97; 95% CI, 1.41 to 2.75), which were primarily at the level of the toe or metatarsal (121). Amputation risk was strongly associated with baseline history of prior amputation and risk factors for amputation (peripheral vascular disease and neuropathy). The risk of amputation was low with 6.3 of participants per 1000 patients-years in the canagliflozin group having an amputation vs. 3.4 in the placebo group. The basis for the increase in amputations is unknown.

However, neither the EMPA-REG OUTCOME trial with empagliflozin nor DECLARE-TIMI 58 trial with dapagliflozin reported an increase in amputations in the patients treated with an SGLT2 inhibitor (120,127,160). Moreover, in the CREDENCE trial, canagliflozin also did not cause an increase in amputations in the patients treated with the SLGT2 inhibitor (126).

A recent review noted that observational studies have been inconclusive with some studies showing an increased risk of amputations in patients on SGLT2 inhibitors, particularly canagliflozin, and other studies failing to show an increase (161).

Given the discordant results in both the randomized controlled trials and observational studies it is difficult to know whether SGLT2 inhibitors, particularly canagliflozin, are associated with an increased risk of amputations and if so, what is the mechanism. Clearly additional studies are required.

Nevertheless, before initiating SGLT2 inhibitor therapy one should consider factors in the patient history that may predispose them to the need for amputations, such as a history of prior amputation, peripheral vascular disease, severe neuropathy and diabetic foot ulcers (package insert).
ACUTE ILLNESS

Because of the risk of hypovolemia, hypotension, and DKA the administration of SGLT2 inhibitors should be suspended during acute illness or planned surgical procedures. SGLT2 inhibitor therapy may be resumed following recovery.

Contraindications and Drug Interactions

RENAieron aL FUNCTION

The dose of canagliflozin needs to be adjusted based on renal function and all SGLT2 inhibitors are contraindicated if the eGFR is less than 30 mL/min/1.73 m². Therefore, renal function needs to be assessed prior to initiating therapy and periodically thereafter.

Canagliflozin is limited to 100 mg once daily in patients with an eGFR of 45 to 60 mL/min/1.73 m² and the drug is not recommended in patients with an eGFR less than 45 mL/min/1.73 m². Canagliflozin is contraindicated in patients with an eGFR less than 30 mL/min/1.73 m².

Dapagliflozin is not recommended in patients with an eGFR less than 60 mL/min/1.73 m² and is contraindicated in patients with an eGFR less than 30 mL/min/1.73 m².

Empagliflozin should not be used in patients with an eGFR less than 45 mL/min/1.73 m².

Ertugliflozin is not recommended in patients with an eGFR less than 60 mL/min/1.73 m² and is contraindicated in patients with an eGFR less than 30 mL/min/1.73 m².

Summary

SGLT2 inhibitors are effective at lowering glucose levels and even more importantly have beneficial effects on cardiovascular disease and renal disease. They have a number of potential side effects but many are not definitively associated with SGLT2 inhibitors (fractures, urinary tract infections, amputations) or are rare (DKA, Fournier’s gangrene). The major side effect is genital mycotic infections, which usually are mild and respond to treatment. In patients with pre-existing cardiovascular disease, at high risk for cardiovascular disease, or with renal disease SGLT2 inhibitors are a leading therapeutic choice.

Table 14. Advantages and Disadvantages of SGLT2 Inhibitors

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight loss</td>
<td>Urinary Tract Infections?</td>
</tr>
<tr>
<td>No hypoglycemia</td>
<td>Genital Mycotic Infections</td>
</tr>
<tr>
<td>Decrease CVD particularly CHF</td>
<td>Increased LDL</td>
</tr>
<tr>
<td>Decreases renal dysfunction</td>
<td>Increased risk of DKA (rare)</td>
</tr>
<tr>
<td>Once a day</td>
<td>Postural hypotension/volume depletion</td>
</tr>
<tr>
<td>Decrease BP</td>
<td>Fractures/ Osteoporosis?</td>
</tr>
<tr>
<td>Once a day administration</td>
<td>Increased risk amputations (canagliflozin)?</td>
</tr>
<tr>
<td>Decrease mortality</td>
<td>Fournier’s gangrene (rare)</td>
</tr>
<tr>
<td></td>
<td>Expensive</td>
</tr>
</tbody>
</table>

DOPAMINE AGONIST (CYCLOSET)

Introduction

In 2009, a quick-release formulation of bromocriptine (Cycloset, bromocriptine-QR) was approved to improve glycemic control in patients with Type 2 diabetes (162,163). Bromocriptine is a centrally-acting dopamine D2 receptor agonist that has been used for many years for the treatment of hyperprolactinemia and Parkinson’s disease (162,163). It can be used to improve glycemic control in patients with Type 2 diabetes either as monotherapy or in combination with other hypoglycemic drugs (162,163)

Administration

Bromocriptine-QR should be initiated at one tablet (0.8 mg) within two hours after waking in the
morning. The dose can be increased by one tablet per week until a maximum daily dose of 6 tablets (4.8 mg) or until the maximal tolerated number of tablets between 2 and 6 per day is reached. Taking bromocriptine-QR with food is recommended to decrease gastrointestinal side effects (162).

Mechanism of Action

Bromocriptine-QR decreases insulin resistance resulting in an increase in glucose disposal and a decrease in hepatic glucose production (162). Bromocriptine-QR does not increase insulin levels (162). Thus, the effectiveness of bromocriptine-QR will be greatest in patients that are insulin resistant and produce insulin (162). Based on animal studies it is thought that bromocriptine-QR acts on the central nervous system, particularly the hypothalamus, to increase insulin sensitivity in liver, muscle, and adipose tissue (162).

Glycemic Efficacy

In a 24 week monotherapy study the A1c level was 0.4% lower in the bromocriptine-QR group compared to placebo group (164). Both fasting and postprandial glucose levels were decreased with bromocriptine-QR treatment (164). Bromocriptine-QR treatment was associated with a decrease in triglyceride levels (32 mg/dL) but no significant change in LDL or HDL cholesterol levels or change in body weight (164). A trial adding bromocriptine-QR to sulfonylurea therapy demonstrated a 0.55% lower A1c in the bromocriptine-QR group compared to placebo (164). As in the monotherapy study fasting glucose, postprandial glucose, and triglyceride levels were decreased with no change in LDL or HDL cholesterol levels (164). Addition of bromocriptine-QR to other hypoglycemic drugs including insulin results in an approximate decrease in A1c of 0.5 to 1.0% (162,163). Hypoglycemia is a rare side effect with use of bromocriptine-QR alone, but is increased with use of insulin secretagogue therapy or insulin (163,164).

Other Effects

BLOOD PRESSURE

Bromocriptine-QR modestly decreases systolic and diastolic blood pressure (163,164).

LIPIDS

Bromocriptine-QR treatment decreases triglyceride levels but has no significant effect on LDL or HDL cholesterol levels (163,164). The decrease in triglyceride levels is thought to be due to a decrease in hepatic triglyceride synthesis, likely due to a decrease in adipose tissue lipolysis resulting in decreased blood free fatty acid levels and decreased delivery of fatty acids to the liver for triglyceride synthesis (162).

CARDIOVASCULAR DISEASE

A 52-week, randomized, double-blind, multicenter trial evaluated cardiovascular safety in 3,095 patients with Type 2 diabetes treated with bromocriptine-QR or placebo (165). The composite end point of first myocardial infarction, stroke, coronary revascularization, or hospitalization for angina or congestive heart failure occurred in 1.8% of the bromocriptine-QR treated vs. 3.2% of the placebo-treated patients resulting in a 40% decrease in cardiovascular events (HR 0.60; CI 0.37– 0.96). Clearly further studies to confirm this finding and to elucidate the mechanism of this beneficial effect are required.

Side Effects

The most common side effect of bromocriptine-QR therapy is nausea which is usually transient and improves with time (163,164). This side effect can be minimized by reducing the dose (163,164). In the pooled phase 3 trial results adverse events leading to discontinuation occurred in 539 (24%) of the bromocriptine-QR treated patients and 118 (9%) of the placebo-treated patients. This between-group difference was driven mostly by gastrointestinal adverse events, particularly nausea (package insert). Similarly, in the bromocriptine-QR safety trial adverse events leading to discontinuation of drug occurred in 24% of the bromocriptine-QR treated patients and 15% of the placebo-treated patients, a difference again driven mostly by gastrointestinal adverse events, particularly nausea (package insert).

Hypotension resulting in syncope can occur particularly in patients on anti-hypertensive medications (package insert). Other side effects
include somnolence, fatigue, vomiting, headache, dizziness (package insert).

**Contraindications and Drug Interactions**

Bromocriptine-QR is metabolized by the Cyp3A4 system and therefore the drug should not be used with strong CYP3A4 inhibitors (e.g., azole antimycotics, HIV protease inhibitors) and the dose should not exceed 1.6 mg once daily during concomitant use of a moderate CYP3A4 inhibitor (e.g., erythromycin) (package insert).

Bromocriptine-QR is contraindicated in patients with syncopal migraine because it increases the likelihood of a hypotensive episode (package insert). The use of bromocriptine-QR in patients with severe psychotic disorders is not recommended as it may exacerbate the disorder or diminish the effectiveness of drugs used to treat the disorder (for example clozapine, olanzapine, ziprasidone) (package insert).

**Summary**

Bromocriptine-QR has modest effects on A1c levels by decreasing insulin resistance. In clinical trials the drug was often discontinued due to nausea. Because of the modest effects on A1c and the prominent side effects this drug is not widely used in the treatment of Type 2 diabetes. If further studies confirmed the decrease in cardiovascular events in patients treated with bromocriptine-QR the use of this drug would increase greatly.

<table>
<thead>
<tr>
<th>Table 15. Advantages and Disadvantages of Bromocriptine-QR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>Decreases triglycerides</td>
</tr>
<tr>
<td>Once a day dosing</td>
</tr>
<tr>
<td>Cardiovascular benefits?</td>
</tr>
<tr>
<td>Decrease BP</td>
</tr>
<tr>
<td>Neutral weight effect</td>
</tr>
<tr>
<td>Hypoglycemia uncommon</td>
</tr>
</tbody>
</table>

**OVERVIEW OF THE INCRETIN SYSTEM**

The incretin effect refers to a greater insulin stimulatory effect after an oral glucose load than from an intravenous glucose infusion when plasma glucose concentrations are matched (166). Thus, glucose and other nutrients delivered via the gastrointestinal tract potentiate the ability of the beta cells in the pancreas to produce insulin resulting in greater insulin secretion than with IV glucose (167). The increase in insulin levels with IV glucose is only approximately one-third of that elicited by oral glucose. The majority of the incretin effect is due to two GI hormones, glucose-dependent insulino tropic peptide (GIP) and glucagon like peptide-1 (GLP-1) with GIP having a dominant role (Figure 6) (166). The basal plasma levels of the incretin hormones are low but after eating the levels increase reaching concentrations that augment the insulin secretory responses if glucose levels are high but are ineffective at low glucose concentrations (i.e. glucose dependent effect) (166).

Patients with Type 2 diabetes have a significant reduction of the incretin effect but GLP-1 and GIP levels in the blood after meals are not reduced in patients with Type 2 diabetes (166). Rather decreased functional beta cell mass and resistance to the effects of GLP-1 and GIP in patients with Type 2 diabetes accounts for the decreased incretin effect (166). Infusion of GIP has a minimal response on insulin secretion in patients with Type 2 diabetes (resistance to effect of GIP) whereas GLP-1 administration is able to stimulate insulin secretion but the response is reduced in patients with Type 2 diabetes compared to normal individuals likely secondary to decreased functional beta cell mass (166). Achieving near-normoglycemia by intensified insulin regimens improved beta cell responsiveness to exogenous GIP and GLP-1, although the increase in insulin secretion was still much lower than those in normal individuals (166). The reduced incretin effect in
patients with Type 2 diabetes occurs after the diagnosis of diabetes is established, suggesting this abnormality is secondary to the diabetic state rather than the cause of diabetes (167).

**Glucagon Like Peptide-1 (GLP-1)**

GLP-1 is cleaved from the pro-glucagon molecule by pro-hormone convertase enzymes in the intestine (167). GLP-1 is stored in the L-cells of the intestine, predominantly in the ileum and colon, and is released at mealtime in response to neurohormonal signals and the presence of food in the gut (166,167). GLP-1 affects postprandial glucose levels through several mechanisms, including enhancing insulin secretion by the beta cells and inhibiting postprandial glucagon secretion by the alpha cells in a glucose-dependent manner (i.e. GLP-1 does not stimulate insulin secretion or inhibit glucagon secretion unless glucose levels are elevated) (167). This glucose dependent effect accounts for why incretin-based drugs do not cause hypoglycemia. Activation of GLP-1 receptors on beta cells increases cAMP levels, which potentiates insulin release in the presence of elevated glucose concentrations. In addition, GLP-1 slows the rate of gastric emptying, which is often paradoxically accelerated in patients with diabetes (167). GLP-1 also acts as a postprandial satiety signal through neurohormonal networks that signal the brain to suppress appetite and food intake, which can lead to weight loss (167). Animal studies suggest that exogenous GLP-1 has the ability to increase islet size, enhance beta-cell proliferation, inhibit beta-cell apoptosis, and regulate islet growth (168). The administration of GLP-1 intravenously increases insulin secretion, reduces glucagon secretion, and decreases glucose levels during fasting and in the post-prandial state (166). GLP-1 is rapidly degraded by dipeptidyl peptidase 4 (DPP-4) into inactive peptides (half-life is minutes) (Figure 6).

![Figure 6. Incretin Hormone Secretion and Effect on Pancreas](image)

**Glucose-Dependent Insulinotropic Peptide (GIP)**

Within minutes after ingestion of food, GIP is secreted from the K-cells located in the proximal region of the jejunum (166,167). GIP helps maintain normal glucose homeostasis by stimulating an increase in insulin secretion by the beta cells (Figure 6). Studies have suggested that the increase in insulin with food intake (Incretin effect) is primarily mediated by GIP (166). In contrast to GLP-1, GIP does not inhibit glucagon secretion, and in fact may stimulate glucagon secretion during euglycemic states. Additionally, GIP has no effect on gastric emptying or on satiety. GIP concentrations in patients with type 2 diabetes are either normal or slightly increased following a meal indicating that the failure to secrete is not the explanation for the decreased incretin effect.
Rather, beta cells in patients with Type 2 diabetes are resistant to GIP. GIP is rapidly degraded by DPP-4 into inactive peptides (half-life is minutes) (Figure 6). The characteristics of GLP-1 and GIP are shown in table 16.

**Table 16. Characteristics of GLP-1 and GIP**

<table>
<thead>
<tr>
<th></th>
<th>GLP-1</th>
<th>GIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post meal levels in patients with diabetes</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Effect on insulin secretion</td>
<td>Stimulates</td>
<td>Stimulates</td>
</tr>
<tr>
<td>Effect on glucagon secretion</td>
<td>Inhibits</td>
<td>No effect or stimulates</td>
</tr>
<tr>
<td>Gastric emptying</td>
<td>Delays</td>
<td>No effect</td>
</tr>
<tr>
<td>Satiety</td>
<td>Induces</td>
<td>No effect</td>
</tr>
<tr>
<td>Degradation by DPP-4</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Dipeptidyl Peptidase-4 (DPP-4) Inhibitors**

**Introduction**

The currently available DPP-4 inhibitors in the US are sitagliptin (Januvia), saxagliptin (Onglyza), linagliptin (Tradjenta), and alogliptin (Nesina). Vildagliptin (Galvus) is available in Europe (169). DPP-4 inhibitors can be used as monotherapy, dual therapy, triple drug therapy, or in combination with insulin (169). These drugs are very similar and the minor differences will be discussed below.

**Administration**

The recommended dose of sitagliptin is 100 mg once daily. In patients with moderate renal impairment (eGFR greater than or equal to 30 mL/min/1.73 m2 but less than 45 mL/min/1.73 m2), the dose of sitagliptin is 50 mg once daily. In patients with severe renal impairment (eGFR less than 30 mL/min/1.73 m2) the dose of sitagliptin is 25 mg once daily.

The recommended dosage of saxagliptin is 2.5 mg or 5 mg once daily with or without food. In patients with a creatinine clearance CrCl ≤50 mL/min the dose of saxagliptin is 2.5 mg.

The recommended dose of linagliptin is 5 mg once daily. No dose adjustment is required for decreased renal function.

The recommended dose of alogliptin is 25 mg once daily with or without food. The dose of alogliptin is 12.5 mg once daily for patients with moderate renal impairment (CrCl ≥30 to <60 mL/min) and 6.25 mg with severe renal impairment (CrCl <30 mL/min).

Renal function should be checked prior to initiating treatment and periodically because dose adjustments are required for all DPP-4 inhibitors except linagliptin.

**Mechanism of Action**

DPP-4 inhibitors increase the concentration and activity of the endogenous incretins, GLP-1 and GIP, by inhibiting the proteolytic cleavage of these hormones by DPP-4, into inactive molecules (169). As discussed above, GLP-1 is secreted by L-cells in the intestines and stimulates insulin secretion and suppresses glucagon secretion in a glucose dependent manner, inhibits gastric emptying, and has central anorexic activity that decreases food intake. GIP is secreted by the K cells in the proximal intestine and stimulates insulin secretion in a glucose dependent manner.

An increase in active GLP-1 and GIP potentiates glucose induced insulin secretion and an increase in GLP-1 inhibits glucagon secretion (169). Together an increase in insulin and a decrease in glucagon will result in a decrease in blood glucose levels. Of note, DPP-4 inhibition results in a 2–3-fold increase in postprandial active GLP-1 levels, which is not at a level that delays gastric emptying or increases satiety and induces weight loss. This is in contrast to GLP-1 receptor agonist administration that results in marked elevations in active GLP1 activity equivalent to a >10-fold increase in GLP-1, which can delay gastric emptying and increase satiety.
Glycemic Efficacy

DPP-4 inhibitors typically reduce A1c levels by 0.5-1.0% and are less effective in lowering A1c compared to metformin, TZDs, SGLT2 inhibitors, and GLP-1 receptor agonists (Table 6) (8,12,169). With regards to sulfonylureas, studies have shown a greater decrease in A1c with sulfonylureas compared to DPP-4 inhibitors in short term studies but in studies greater than one year the effect of sulfonylureas and DPP-4 inhibitors on A1c were similar (8,169). The ability of DPP-4 inhibitors to lower A1c is similar in monotherapy and when DPP-4 inhibitors are used in combination with other drugs (8,169). The decrease in A1c is similar for the different DPP-4 inhibitors (8,12). DPP-4 inhibitors are effective in lowering postprandial glucose levels. Because of their mechanism of action, DPP-4 inhibitors do not cause hypoglycemia but can potentiate the hypoglycemia induced by insulin or sulfonylureas (8,169). An adjustment in the dose of sulfonylureas or insulin may be required to reduce the risk of hypoglycemia.

Other Effects

WEIGHT

DPP-4 inhibitors are weight neutral (8,169).

BLOOD PRESSURE

A meta-analysis of 15 trials involving 5636 participants found that DPP-4 inhibitors compared to placebo reduced systolic BP (mean difference, -3.04 mmHg; P<0.00001) and diastolic BP (mean difference, -1.47 mmHg; P<0.00001) (170).

CARDIOVASCULAR DISEASE

The effect of the DPP-4 inhibitors saxagliptin, alogliptin, sitagliptin, and linagliptin on cardiovascular endpoints has been reported. In the saxagliptin study (SAVOR-TIMI 53 trial), 16,492 patients with Type 2 diabetes who had a history of cardiovascular events or who were at high risk were randomized to saxagliptin or placebo for 2.1 years (171). Saxagliptin did not increase or decrease cardiovascular death, myocardial infarction, or ischemic stroke. Interestingly more patients treated with saxagliptin were admitted to the hospital for heart failure. The risk of heart failure with saxagliptin was greatest in patients at a high overall risk of heart failure (i.e., history of heart failure, impaired renal function, or elevated baseline levels of NT-proBNP) (172). Additionally, in the patients treated with saxagliptin the increase in heart failure was an early event with a 6-month rate of 1.1% vs. 0.6% in the placebo group (HR 1.80, p=0.001) and a 12 month rate of 1.9% vs. 1.3% (1.46; p=0.002) (172). In contrast, after 12 months no difference in the rate of heart failure was observed in the saxagliptin and placebo groups indicating that the development of heart failure is an early event (172).

In the alogliptin trial (EXAMINE), 5380 patients with either an acute myocardial infarction or unstable angina within the previous 15-90 days were randomized to alogliptin or placebo and followed for a median of 18 months (173). As seen in the saxagliptin study the rates of cardiovascular events (death from cardiovascular causes, non-fatal myocardial infarction, or non-fatal stroke) were similar in the alogliptin and placebo groups. The risk of hospitalization for heart failure was not statistically increased in the entire subset of patients treated with alogliptin (174). However, the hazard ratio for the subgroup of patients without heart failure at baseline was 1.76, p=0.026 (174).

In the sitagliptin trial (TECOS), 14,671 patients with established cardiovascular disease were randomized to sitagliptin or placebo for 3 years (175). Sitagliptin did not decrease the risk of major adverse cardiovascular events or increase hospitalization for heart failure. Finally, in the linagliptin trial (CARMELINA), 6979 patients at high risk for cardiovascular disease were randomized to linagliptin or placebo for a median follow-up of 2.2 years (176). As in the other DPP-4 inhibitor studies, linagliptin did not have a beneficial effect on cardiovascular events. Additionally, linagliptin did not increase the risk of hospitalization for heart failure (177). Thus, these results indicate that DPP-4 inhibitors do not reduce cardiovascular disease. The effect of DPP-4 inhibitors on the development of heart failure needs further investigation and whether specific DPP-4 inhibitors increase the risk of heart failure remains to be resolved.

RENAL DISEASE

Changes in renal function were examined in the large cardiovascular outcome trials described
above. In the SAVOR-TIMI 53 trial treatment with saxagliptin decreased albuminuria but had no effect on eGFR (178). Saxagliptin reduced the development of macroalbuminuria independent of changes in A1c levels (171,178). Doubling of serum creatinine, initiation of chronic dialysis, renal transplantation, or serum creatinine >6.0 mg/dL, were similar in the saxagliptin and placebo groups (178). In the TECOS trial treatment with sitagliptin also reduced the urinary albumin to creatinine ratio with no effect on eGFR (179). In the CARMELINA trial many of the patients had pre-existing renal disease (74% of patients had prevalent diabetic kidney disease, 43% had an eGFR below 45 mL/min/1.73 m2, 15.2% had an eGFR below 30 mL/min/1.73 m2 and 80% had a urinary albumin creatinine ratio >30 mg/g) (176). Treatment with linagliptin reduced the progression of albuminuria but had no effect on death due to renal failure, ESRD, or sustained 40% or higher decrease in eGFR from baseline (176).

Taken together these studies indicate that DPP-4 inhibitors decrease proteinuria but do not provide data suggesting an improvement or delay in worsening of renal function.

**Side Effects**

DPP-4 inhibitors have been safe drugs with minimal side effects and are well tolerated by patients. Very rarely hypersensitivity reactions including urticaria, facial edema, anaphylaxis, angioedema, and exfoliative skin conditions including Stevens-Johnson syndrome have occurred (package insert). Bullous pemphigoid has also rarely been associated with DPP-4 inhibitor treatment (package insert).

**ACUTE PANCREATITIS**

The package insert of DPP-4 inhibitors indicates that acute pancreatitis is a complication of DPP-4 inhibitor treatment. The individual results of the SAVOR–TIMI, EXAMINE, and TECOS trials discussed above did not show an increased risk of pancreatitis or pancreatic cancer. However, two meta-analysis of these studies demonstrated an 80% increased risk of acute pancreatitis in patients using DPP-4 inhibitors compared with those receiving standard care (180,181). It should be noted that the absolute risk was small (0.13%), which would result in one to two additional cases of acute pancreatitis for every 1,000 patients treated for 2 years (181). Thus, pancreatitis appears to be a rare side effect of DPP-4 inhibitors. In patients on DPP-4 inhibitors who have GI symptoms suggestive of pancreatitis further evaluation is indicated. The diagnosis of acute pancreatitis requires the presence of two of the following three criteria: acute onset of persistent, severe, epigastric pain often radiating to the back, elevation in serum lipase or amylase to three times or greater than the upper limit of normal, and characteristic findings of acute pancreatitis on imaging (182).

**ARTHRALGIA**

Severe and disabling arthralgia in patients taking DPP-4 inhibitors has been reported (183). The time to onset of symptoms following initiation of drug therapy varied from one day to years. Patients experienced relief of symptoms upon discontinuation of the medication and a subset of patients experienced a recurrence of symptoms when restarting the same drug or a different DPP-4 inhibitor. If a patient develops severe joint pain discontinue the DPP-4 inhibitor.

**Contraindications and Drug Interactions**

It is unknown whether patients with a history of pancreatitis or who are at increased risk for the development of pancreatitis should be started on DPP-4 inhibitors. Given the availability of other hypoglycemic drugs many clinicians avoid the use of DPP-4 inhibitors in these patients.

The dosage of saxagliptin is 2.5 mg once daily when co-administered with a strong cytochrome P450 3A4/5 inhibitors (e.g., ketoconazole, atazanavir, clarithromycin, indinavir, itraconazole, nefazodone, nelfinavir, ritonavir, saquinavir, and telithromycin) (package insert).

**Summary**

DPP-4 inhibitors, while not the most potent drugs at lowering A1c, nevertheless are very attractive to use in the treatment of patients with Type 2 diabetes as they are safe drugs that do not have many side effects. They do not cause hypoglycemia, weight gain, or cardiovascular disease.
Table 17. Advantages and Disadvantages of DPP-4 Inhibitors

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>No hypoglycemia</td>
<td>Pancreatic disease</td>
</tr>
<tr>
<td>Weight neutral</td>
<td>Heart failure hospitalization (saxagliptin/alogliptin)</td>
</tr>
<tr>
<td>Decreases postprandial glucose</td>
<td>Arthritis</td>
</tr>
<tr>
<td>Once a day</td>
<td>Bullous pemphigoid</td>
</tr>
<tr>
<td>Well tolerated</td>
<td>Relatively expensive</td>
</tr>
<tr>
<td>Decreases BP</td>
<td>Modest glycemic lowering</td>
</tr>
</tbody>
</table>

GLUCAGON LIKE PROTEIN-1 (GLP-1) RECEPTOR AGONISTS

Introduction

There are currently six GLP-1 receptor agonists available in the US, three drugs administered daily and three drugs administered weekly (Figure 7). Albiglutide (Tanzeum) was withdrawn from the market for commercial reasons and is no longer available. GLP-1 receptor agonists can be used in combination with multiple oral anti-diabetic drugs or in combination with insulin (184). The concentrations of GLP-1 receptor agonist activity is much higher than physiological levels of GLP-1 activity (8). The GLP-1 receptor agonists that are similar to exendin-4 (Exenatide and Lixisenatide) are eliminated by the kidneys and therefore in patients with severe renal disease these drugs are contraindicated (8). In contrast, the drugs that are analogues of GLP-1 are degraded by peptidases (8).

Figure 7. Structure of GLP-1 Receptor Agonists

SHORT ACTING GLP-1 RECEPTOR AGONISTS

Exenatide (Byetta) is a synthetic exendin-4 that is a peptide originally isolated from the saliva of the Gila monster that has a 53% homology with human GLP-1 and is resistant to degradation by DPP-4 (8,184). Lixisenatide (Adylyxin) is an exendin-4 analogue with six Lys residues added at the C terminus to confer resistance to DPP-4 (8,184).

LONG ACTING GLP-1 RECEPTOR AGONISTS

Even though liraglutide (Victoza) is administered daily it is considered a long acting GLP-1 receptor
agonist because its effects on fasting glucose are similar to weekly GLP-1 receptor agonists and its effects on gastric emptying wane as seen with weekly GLP-1 receptor agonists. Liraglutide is an analogue of GLP-1 with the addition of a 16-carbon fatty acid chain that masks the DPP-4 cleavage site preventing degradation (8,179). Once weekly exenatide (Bydureon and Bydureon BCise) is a sustained-release formulation that consists of exenatide embedded within biodegradable polymeric microspheres of poly (DL-lactic-co-glycolic acid) (8). Dulaglutide (Trulicity) has two copies of a GLP-1 analogue covalently linked to an Fc fragment of human IgG4 (8,184). Semaglutide (Ozempic) is an analogue of human GLP-1 RA and is linked via a hydrophilic spacer and a fatty acid side chain to albumin (184).

**Administration**

**SHORT ACTING GLP-1 RECEPTOR AGONISTS**

Initiate exenatide at 5 ug twice daily; increase to 10 ug twice daily after 1 month based on clinical response. Inject subcutaneously within 60 minutes prior to morning and evening meals (or before the two main meals of the day).

The starting dose of lixisenatide is 10 ug subcutaneously once daily within one hour before the first meal of the day for 14 days and then increase the dose to the maintenance dose of 20 ug once daily.

**LONG ACTING GLP-1 RECEPTOR AGONISTS**

Initiate liraglutide with a dose of 0.6 mg per day for one week. After one week at 0.6 mg per day, the dose should be increased to 1.2 mg. If the 1.2 mg dose does not result in acceptable glycemic control, the dose can be increased to 1.8 mg. Inject subcutaneously once-daily at any time of day, independently of meals.

The recommended dose of long acting exenatide is 2 mg subcutaneously once every 7 days (weekly). The dose can be administered at any time of day, with or without meals.

The recommended initiating dose of dulaglutide is 0.75 mg subcutaneously with or without food once weekly. The dose may be increased to 1.5 mg once weekly for additional glycemic control.

The recommended initiating dose of semaglutide is 0.25 mg subcutaneous injection with or without food once weekly for 4 weeks. The 0.25 mg dose is intended for treatment initiation and is not effective for glycemic control. After 4 weeks on the 0.25 mg dose, increase the dosage to 0.5 mg once weekly. If additional glycemic control is needed after at least 4 weeks on the 0.5 mg dose, the dosage may be increased to 1 mg once weekly.

Note that exenatide and lixisenatide are contraindicated in patients with renal dysfunction (for details see Contraindications section).

**Mechanism of Action**

GLP-1 receptor agonists potentiate glucose dependent insulin secretion increasing insulin levels and lowering glucose levels (8). In addition, GLP-1 receptor agonists potentiate the glucose dependent inhibition of glucagon secretion, which will also lower glucose levels (8). Finally, because of the supraphysiological levels of GLP-1 activity, short-acting GLP-1 receptor agonists will delay gastric emptying resulting in a decrease in postprandial glucose levels and induce satiety, which will decrease food intake (8).

**Glycemic Efficacy**

GLP-1 receptor agonists typically lower A1c by 1-2% (8). The efficacy of GLP-1 receptor agonists vary with semaglutide being the most potent and lixisenatide being the least potent (see table 6) (12). In general, long acting GLP-1 receptor agonists are better at lowering A1c levels compared to short acting agents (12,184). The efficacy in lowering A1c is similar in monotherapy and during combination therapy (8). The reduction in A1c is sustained over several years (164). Long acting GLP-1 receptor agonists lower fasting glucose levels more effectively than short acting drugs (184). Conversely, short acting GLP-1 receptor agonists lower postprandial glucose excursions to a greater extent than long acting agents (184). Short acting GLP-1 receptor agonists induce a substantial retardation in gastric emptying, which likely contributes significantly to the markedly lowering postprandial glucose excursions after meals when
they are administered (184). Notably, the ability of short acting GLP-1 receptor agonists to prevent postprandial glucose excursions is greatly diminished for meals when they are not administered (184). In patients with diminished beta cell function the glycemic response to GLP-1 receptor agonist therapy is reduced (185).

Studies have compared adding a GLP-1 receptor agonist to basal insulin vs. adding rapid acting insulin to basal insulin (186). In a meta-analysis there were no differences in lowering A1c levels but treatment with basal insulin plus GLP-1 receptor agonist led to a significant reduction in body weight, whereas basal insulin plus rapid acting insulin treatment was associated with weight gain (difference -2.95 kg; p = 0.0001) (186). Additionally, patients treated with basal insulin plus GLP-1 receptor agonist were less likely to experience symptomatic hypoglycemia (OR: 0.52; p < 0.0001) and severe hypoglycemia (OR: 0.27; p = 0.07) than those treated with basal insulin plus rapid acting insulin. Thus, adding a GLP-1 receptor agonist to basal insulin instead of bolus insulin will result in similar improvements in glycemic control with fewer side effects.

Studies have also compared adding insulin therapy vs. adding a GLP-1 receptor agonist. In a meta-analysis of 19 studies GLP-1 receptor agonists reduced A1c levels slightly more than insulin therapy (difference -0.12%, P < .0001) (187). As expected, hypoglycemia was less frequent in the patients treated with the GLP-1 receptor agonists.

Because the effect of GLP-1 receptor agonists on insulin and glucagon secretion are glucose dependent they have a low potential to cause hypoglycemia (8,184). The risk of hypoglycemia increases when these GLP-1 receptor agonists are used in combination with insulin or secretagogues (184).

Other Effects

WEIGHT LOSS

GLP-1 receptor agonists induce weight loss (8,184). A comparison of the ability of the maximum dose of different GLP-1 receptor analogues to induce weight loss are shown in table 18. It should be recognized that the weight loss shown in Table 18 represents averages. In clinical practice some patients lose a large amount of weight with GLP-1 receptor agonists while other patients can actually gain weight. The author has personally seen patients’ loss more than 50 lbs. The exact mechanisms responsible for the decrease in weight are not yet fully understood but both central and peripheral mechanisms are thought to play a part in activating receptors in the central nervous system associated with weight loss (184). GLP-1 receptor agonists are thought to reduce body weight through decreased gastrointestinal motility and the promotion of satiety via the activation of GLP-1 receptors in various regions of the brain (184).

Table 18. Effect of GLP-Receptor Agonists on Weight Loss (12)

<table>
<thead>
<tr>
<th>GLP-1 Receptor Agonist</th>
<th>Weight Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dulaglutide 1.5mg weekly</td>
<td>1.1Kg</td>
</tr>
<tr>
<td>Exenatide 10ug bid</td>
<td>1.2Kg</td>
</tr>
<tr>
<td>Exenatide 2mg weekly</td>
<td>1.1Kg</td>
</tr>
<tr>
<td>Liraglutide 1.8mg qd</td>
<td>1.5Kg</td>
</tr>
<tr>
<td>Lixisenatide 20ug qd</td>
<td>0.7Kg</td>
</tr>
<tr>
<td>Semaglutide 1mg weekly</td>
<td>3.8Kg</td>
</tr>
</tbody>
</table>

Based on a baseline weight of 90 kg after 26 weeks of treatment

BLOOD PRESSURE

GLP-1 receptor agonists result in modest but significant reductions in systolic blood pressure (2-5 mmHg) (8).

HEART RATE

The effects of GLP-1 receptor agonists on heart rate differ between drugs. Short-acting GLP-1 receptor agonists result in a modest (1-3 beats per minute) while long-acting GLP-1 receptor agonists...
are associated with a more pronounced and sustained increase (3-10 beats per minute) during the day and night (188).

**CARDIOVASCULAR DISEASE**

The effect of six GLP-1 receptor agonists on cardiovascular disease has been reported.

**ELIXA**

In the Elixa trial 6068 patients with Type 2 diabetes and who recently had a myocardial infarction or been hospitalized for unstable angina were randomized to placebo or lixisenatide, and followed for a median of 25 months (189). The primary end point of cardiovascular death, myocardial infarction, stroke, or hospitalization for unstable angina was similar in the placebo or lixisenatide groups.

**LEADER Trial**

In contrast, the LEADER trial has shown that liraglutide decreased cardiovascular events (190). In this trial 9340 patients at high cardiovascular risk were randomly assigned to receive liraglutide or placebo. After median time of 3.5 years, the primary outcome of death from cardiovascular causes, nonfatal myocardial infarction, or nonfatal stroke occurred in significantly fewer patients in the liraglutide group (13.0%) than in the placebo group (14.9%) (hazard ratio, 0.87; P=0.01). Additionally, deaths from cardiovascular causes (hazard ratio 0.78, P=0.007) or any cause was lower in the liraglutide group than in the placebo group (hazard ratio, 0.85; P=0.02). Interestingly patients with established cardiovascular disease or decreased renal function (eGFR < 60) appeared to derive the greatest benefit of liraglutide treatment (191,192). As expected, weight and blood pressure were decreased in the liraglutide treated group and A1c levels were also decreased by 0.4%.

**SUSTAIN 6 Trial**

In support of the beneficial effects of some GLP1 receptor agonists to reduce cardiovascular events, semaglutide, a long acting GLP-1 receptor agonist, has also been shown to reduce cardiovascular events (193). In this trial, 3297 patients with Type 2 diabetes with established cardiovascular disease, chronic heart failure, chronic kidney disease, or age >60 with at least one cardiovascular risk factor were randomized to receive once-weekly semaglutide (0.5 mg or 1.0 mg) or placebo for 104 weeks. The primary outcome of cardiovascular death, nonfatal myocardial infarction, or nonfatal stroke occurred in 6.6% of the semaglutide group and 8.9% of the placebo group (hazard ratio, 0.74; P = 0.02). In this study, both body weight and A1c levels were decreased in the patients treated with semaglutide.

**EXSCEL Trial**

The effect of once weekly exenatide vs. placebo on cardiovascular outcomes was tested in 14,752 patients, 73% who had cardiovascular disease (194). The primary outcome was the occurrence of death from cardiovascular causes, nonfatal myocardial infarction, or nonfatal stroke. After a median follow-up of 3.2 years (duration of drug exposure 2.4 years) the primary outcome was reduced in the exenatide treated group but this difference just missed achieving statistical significance (hazard ratio 0.91; 95% CI 0.83-1.00; p=0.06). While not statistically significant these results are consistent with the results observed with liraglutide and semaglutide treatment. It should be recognized that a high percentage of patients discontinued exenatide therapy in this trial (>40%) and this could have adversely affected the ability of exenatide treatment to favorably effect cardiovascular outcomes.

**HARMONY Outcomes Trial**

The effect of once weekly albiglutide vs. placebo was tested in 9,463 patients with cardiovascular disease (195). The primary outcome was first occurrence of cardiovascular death, myocardial infarction, or stroke. After a median follow-up of 1.6 years a 22% decrease in the primary endpoint was observed in the albiglutide group (hazard ratio 0.78, p<0.0001). It should be noted that albiglutide is no longer available as it was removed from the market due to commercial considerations by Glaxo.

**REWIND Trial**

The effect of once weekly albiglutide vs. placebo was tested in 9,463 patients with cardiovascular disease (195). The primary outcome was first occurrence of cardiovascular death, myocardial infarction, or stroke. After a median follow-up of 1.6 years a 22% decrease in the primary endpoint was observed in the albiglutide group (hazard ratio 0.78, p<0.0001). It should be noted that albiglutide is no longer available as it was removed from the market due to commercial considerations by Glaxo.
This was a randomized study of weekly subcutaneous injection of dulaglutide (1.5 mg) or placebo in 9901 patients with diabetes who had either a previous cardiovascular event or cardiovascular risk factors (approximately 70% of patients did not have prior cardiovascular disease) (196). During a median follow-up of 5.4 years the primary outcome of non-fatal myocardial infarction, non-fatal stroke, or death from cardiovascular causes was decreased by 12% in the dulaglutide treated group (HR 0.88, p=0.026). The decrease in events was similar in participants with and without previous cardiovascular disease.

Summary

Thus, four studies have clearly demonstrated that treatment with GLP-1 receptor agonists reduces cardiovascular events, one study has provided data consistent with these results, and one study failed to demonstrate benefit. Why there are differences in results between these studies is unknown but could be due to differential effects of the GLP-1 receptor agonists, differences in the patient populations studied, or other unrecognized variables. The mechanism accounting for this decrease in cardiovascular disease is uncertain but could be related to reductions in glycated hemoglobin, body weight, systolic blood pressure, or the direct effect of activation of GLP-1 receptors on the atherosclerotic process.

HEART FAILURE

Two small randomized studies have examined the effect of GLP-1 receptor agonists on clinical outcomes in patients with heart failure. Margulies and colleagues randomized patients recently hospitalized for heart failure with a decreased ejection fraction to liraglutide (n=154) or placebo (n=146) (59% with Type 2 diabetes) (197). Treatment with liraglutide did not lead to greater posthospitalization clinical stability or decrease the number of deaths or rehospitalizations for heart failure. Jorsal et al carried out a randomized trial of liraglutide vs. placebo in patients (n=241) with reduced left ventricular ejection fraction who were clinically stable and on optimal heart failure treatment (198). Unexpectedly, serious cardiac events were seen in 10% of patients treated with liraglutide compared with 3% of patients in the placebo group (P = 0.04). Thus, the effect of GLP-1 receptor agonists in patients with heart failure requires further study.

RENAL DISEASE

Five of the cardiovascular outcome studies described above also examined the effect of GLP-1 receptor agonists on kidney disease.

ELIXA Trial

Lixisenatide treatment decreased urinary albumin-to-creatinine ratio in patients with pre-existing micro or macroalbuminuria (199). Additionally, lixisenatide was associated with a reduced risk of new-onset macroalbuminuria compared with placebo (199). However, no significant differences in eGFR decline or the number of patients doubling their serum creatinine levels were seen between the lixisenatide treated group vs. placebo group (199).

LEADER Trial

The renal outcome in this trial was a composite of new-onset persistent macroalbuminuria, persistent doubling of the serum creatinine level, end-stage renal disease, or death due to renal disease, which occurred in fewer patients in the liraglutide group than in the placebo group (hazard ratio, 0.78; P=0.003) (200). This favorable outcome was driven primarily by a decrease in the development of macroalbuminuria. The renal benefits did not appear to be driven by changes in A1c, body weight, or decreases in systolic BP.

SUSTAIN 6 Trial

In this trial, new or worsening nephropathy, defined as persistent macroalbuminuria, persistent doubling of the serum creatinine, or a creatinine clearance < 45ml/min/1.73m2, occurred in 3.8% of the patients in the semaglutide group and 6.1% of the patients in the placebo group (hazard ratio, 0.64; P=0.005) (193). As seen in the LEADER trial this favorable outcome was driven primarily by a decrease in the development of macroalbuminuria.

EXSCEL Trial

Exenatide treatment resulted in a reduction in new-onset macroalbuminuria compared with placebo.
(2.2% vs 2.8%, P = 0.031), with no significant changes in either microalbuminuria (7.2% vs 7.5%) or ESKD requiring renal replacement therapy (0.7% vs 0.9%) (194).

**REWIND Trial**

The renal outcome included the occurrence of new macroalbuminuria (UACR >33.9 mg/mmol), a sustained decline in eGFR of 30% or more from baseline, or chronic renal replacement therapy (201). During a median follow-up of 5.4 years the renal outcome developed in 17.1% of patients in the dulaglutide group and in 19.6% of patients in the placebo group (HR 0.85, p=0.0004). This beneficial effect was driven by a reduction in the development of macroalbuminuria (HR 0.77; p<0.0001).

**Summary**

These studies demonstrate that GLP-1 receptor agonist administration reduce albuminuria without effecting eGFR. The decrease in albuminuria without effecting eGFR is similar to what was observed in some of the DPP-4 inhibitor studies described above. The mechanism accounting for this decrease is uncertain but decreased systolic BP, weight loss, improved glycemic control, or direct effects on the kidneys could have contributed to this decrease in albuminuria.

**NONALCOHOLIC FATTY LIVER DISEASE (NAFLD) AND NONALCOHOLIC STEATOHEPATITIS (NASH)**

Studies have suggested that GLP-1 receptor agonists have beneficial effects on NAFLD and NASH (85). A meta-analysis of liraglutide and a separate meta-analysis of lixisenatide have reported that these drugs decrease liver enzymes (202,203). A 12-week randomized trial in 60 patients with NAFLD of exenatide + basal insulin vs. rapid acting insulin + basal insulin demonstrated lower liver enzymes in the exenatide treated group (204). Moreover, the reversal rate of fatty liver was greater in the group treated with exenatide (93.3%) than the intensive insulin group (66.7%) (p < 0.01).

In the LEAN Trial 52 patients with NASH were randomized to liraglutide 1.8 mg daily or placebo and followed for 48 weeks (205). Resolution of NASH occurred in 39% of patients treated with liraglutide and only 9% patients in the placebo group (RR 4.3; p=0.019). Progression of fibrosis occurred in 9% of patients in the liraglutide group versus 36% patients in the placebo group (p=0.04).

While these data are suggestive larger and longer studies on the effect of GLP-1 receptor agonists on NAFLD and NASH are required.

**Side Effects**

**GASTROINTESTINAL**

The most common adverse effects are GI and include nausea, vomiting, and diarrhea (184). These symptoms are usually transient, resolving overtime (8). The GI side effects can be reduced by slowly increasing the dose (8). GI side effects tend to be more pronounced with short acting GLP-1 receptor agonists (184). Dehydration can occur secondary to GI side effects and can result in acute kidney failure (package insert).

**INJECTION-SITE REACTIONS**

Injection-site reactions (rash, erythema) are also common with GLP-1 receptor agonists (8). Subcutaneous injection-site nodules may occur with the use of weekly exenatide (package insert), an abnormality that is due to the formulation.

**MEDULLARY THYROID CANCER**

Thyroid C-cell hyperplasia and medullary cell carcinoma has also been raised as possible concerns based on preclinical studies in rodents, but clinical studies in humans have not shown any indication of thyroid disorders (8). A meta-analysis of the four large cardiovascular outcome studies described above did not demonstrate an increased risk of medullary thyroid cancer with GLP-1 receptor agonist treatment (206).

**PANCREATITIS**

Subclinical increases in pancreatic enzyme levels are commonly observed with all GLP-1 receptor agonists and pancreatitis has been reported (184). Importantly increases in lipase and amylase were
not predictive of subsequent pancreatitis (207). A meta-analysis of four large cardiovascular outcome studies described above did not demonstrate an increased risk of pancreatitis or pancreatic cancer with GLP-1 receptor agonist treatment (206,208).

RETINOPATHY

In the SUSTAIN 6 trial described above the rates of retinopathy complications (vitreous hemorrhage, blindness, or conditions requiring treatment with an intravitreal agent or photocoagulation) were significantly higher in the semaglutide group compared to the placebo group (hazard ratio, 1.76; P=0.02) (193). This increased risk of retinopathy complications has been attributed to the magnitude and rapidity of A1c reduction during the first 16 weeks of treatment in patients who had pre-existing retinopathy and poor glycemic control at baseline (209). Of note, other trials using semaglutide did not observe an increased risk of retinopathy (209). Additionally, an increase in diabetic retinopathy was not observed in the other cardiovascular outcome trials (189,190,194,195). Thus, it does not appear that GLP-1 receptor agonists treatment result in an increase in diabetic eye disease.

Contraindications and Drug Interactions

RENA L

Care needs to be exercised in patients with severe renal disease as they are more susceptible to the side effects of GLP-1 receptor agonists and more likely to have serious side effects (package inserts). There is limited data in patients with end stage renal disease.

Exenatide should not be used in patients with severe renal impairment (creatinine clearance < 30 mL/min) or end-stage renal disease (package insert). Caution should be applied when initiating or escalating doses of exenatide from 5 mcg to 10 mcg in patients with moderate renal impairment (creatinine clearance 30 to 50 mL/min) (package insert).

Weekly exenatide is not recommended for use in patients with eGFR below 45 mL/min/1.73m2 or end stage renal disease (package insert).

Lixisenatide is not recommended in patients with end stage renal disease (eGFR <15 mL/min/1.73 m2) (package insert).

No dose adjustments for lixisenatide, semaglutide, or dulaglutide are recommended for patients with renal impairment (package insert).

OTHER

Exenatide is not recommended in patients with gastroparesis or severe gastrointestinal disease (package insert).

In patients with a history of pancreatitis many clinicians avoid GLP-1 receptor agonists.

GLP-1 receptor agonists are contraindicated in patients with a personal or family history of Medullary Thyroid Cancer and in patients with Multiple Endocrine Neoplasia syndrome type 2 (MEN 2) (package insert).

Summary

The ability of GLP-1 receptor agonists to effectively decrease A1c levels, reduce atherosclerotic cardiovascular disease, and in some patients induce a major loss of weight make these drugs very attractive in the treatment of patients with Type 2 diabetes. Additionally, once weekly administration for certain drugs in this class can improve compliance.
Table 19. Advantages and Disadvantages of GLP-1 Receptor Agonists

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Loss</td>
<td>GI side effects</td>
</tr>
<tr>
<td>No Hypoglycemia</td>
<td>Requires Injection</td>
</tr>
<tr>
<td>Reduce CVD (liraglutide, semaglutide, dulaaglutide)</td>
<td>Pancreatitis?</td>
</tr>
<tr>
<td>Improve NASH</td>
<td>Thyroid cancer?</td>
</tr>
<tr>
<td>Once a week therapy possible</td>
<td>Expensive</td>
</tr>
<tr>
<td>Decrease albuminuria</td>
<td></td>
</tr>
<tr>
<td>Decrease postprandial glucose</td>
<td></td>
</tr>
</tbody>
</table>

INSULIN-GLP-1 RECEPTOR AGONIST COMBINATIONS

Introduction

There are currently two insulin-GLP-1 receptor agonist combinations available for use; glargine insulin/lixisenatide (iGlarLixi) (Soliqua) and degludec insulin/liraglutide (iDegLira) (Xultophy). Both combine a basal insulin with a once a day GLP-1 receptor agonist. iGlarLixi contains 100U glargine and 33 ug lixisenatide per ml. iDegLira contains 100U degludec insulin and 3.6 mg liraglutide per ml.

Administration

In patients naive to basal insulin or to a GLP-1 receptor agonist, currently on a GLP-1 receptor agonist, or currently on less than 30 units of basal insulin daily the recommended starting dosage of iGlarLixi 100/33 is 15 units (15 units insulin glargine/5 ug lixisenatide) given subcutaneously once daily. In patients currently on 30 to 60 units of basal insulin daily, with or without a GLP-1 receptor agonist the recommended starting dosage of iGalLixi 100/33 is 30 units (30 units insulin glargine/10 ug lixisenatide) given subcutaneously once daily. After starting with the recommended dose, titrate the dosage upwards or downwards by two to four units weekly based on the patient’s glycemic control until the desired fasting plasma glucose is achieved. Administer iGlarLixi 100/33 subcutaneously once a day within an hour prior to the first meal of the day. The maximum dose of iGlarLixi 100/33 is 60 units daily (60 units insulin glargine/20 ug lixisenatide).

In patients naive to basal insulin or to a GLP-1 receptor agonist therapy the recommended starting dose of iDegLira 100/3.6 is 10 units (10 units of insulin degludec and 0.36 mg of liraglutide) given subcutaneously once-daily. In patients currently on basal insulin or a GLP-1 receptor agonist the recommended starting dose of iDegLira 100/3.6 is 16 units (16 units of insulin degludec and 0.58 mg of liraglutide) given subcutaneously once-daily. After starting the recommended starting dose, titrate the dosage upwards or downwards by two units every three to four days based on the patient’s blood glucose monitoring results and glycemic control goal until the desired fasting plasma glucose is achieved. Administer iDegLira 100/3.6 by subcutaneous injection once-daily at the same time each day with or without food. The maximum dose of iDegLira 100/3.6 is 50 units daily (50 units of insulin degludec and 1.8 mg of liraglutide).

Mechanism of Action

Basal insulin regulates fasting blood glucose levels between meals and overnight while a GLP-1 receptor agonist lowers postprandial glucose levels (210). Together this drug combination results in 24-hour glycemic control.

Glycemic Efficacy

A number of studies have compared the ability of the combination of insulin-GLP receptor agonists to lower A1c levels compared to either insulin alone or GLP-1 receptor agonist alone (210). Table 20 shows the results of two large studies. As shown in Table 20 combination therapy was better at lowering A1c levels compared to the individual components (210). Additionally, the risk of hypoglycemia was similar with combination therapy compared to basal insulin alone. In a study of patients poorly controlled on glargine insulin adding rapid acting insulin (basal/bolus therapy) vs. switching to iDegLira was found to result in a similar reduction in A1c levels but the risk of hypoglycemia was greater with basal/bolus insulin (211). Not unexpectedly basal/bolus insulin resulted in greater
weight gain (difference 3.6 kg) (211). Indirect comparisons suggest that iDegLira reduces A1C slightly more (< 0.5%) than iGlarLixi but this could be due to different study design, different patient populations, or other differences between the trials (210). A meta-analysis of 8 studies concluded that iDegLira and iGlarLixi demonstrated no significant differences in absolute HbA1c changes, fasting plasma glucose levels, or body weight changes relative to baseline (212).

<table>
<thead>
<tr>
<th>Study</th>
<th>Treatment</th>
<th>A1c Reduction</th>
<th>% Subjects with Hypoglycemia</th>
<th>Change in Body Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rosenstock et al (213)</td>
<td>iGlarLixi</td>
<td>1.6%</td>
<td>26</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>Glar</td>
<td>1.3%</td>
<td>24</td>
<td>+1.1</td>
</tr>
<tr>
<td></td>
<td>Lixi</td>
<td>0.9%</td>
<td>6</td>
<td>-2.3</td>
</tr>
<tr>
<td>Gough et al (214)</td>
<td>iDegLira</td>
<td>1.9%</td>
<td>32</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>Deg</td>
<td>1.4%</td>
<td>39</td>
<td>+1.6</td>
</tr>
<tr>
<td></td>
<td>Lira</td>
<td>1.3%</td>
<td>7</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

Other Effects

As shown in Table 20 the typical weight gain seen with insulin therapy alone is blunted with combination therapy.

Side Effects

Studies have noted that the typical GI side effects seen with GLP-1 receptor agonist therapy is blunted with combination therapy (126). The likely explanation is that the titration of the GLP-1 receptor agonist is slower with combination therapy (126).

Contraindications

The maximum daily insulin dose of 60 units for iGlarLixi and 50 units for iDegLira, may not be sufficient in patients requiring higher daily basal insulin doses (e.g., patients with severe insulin resistance). The maximum dose is determined by the GLP-1 receptor agonist dose (the max dose of iDegLira delivers 1.8 mg of liraglutide while the max dose of iGlarLixa delivers 20 ug of lixisenatide). Conversely, there may be some patients who require only a low dose of basal insulin and thus the because of the fixed ratio of basal insulin to GLP-1 receptor agonist the dose of the GLP-1 receptor agonist may be too low. These examples are a limitation of fixed ratio delivery systems. In these patients one can use basal insulin and a GLP-1 receptor agonist independently. It should be noted that for the majority of patients the fixed ratio will be acceptable.

Summary

The effects of combination therapy are predictable based on studies of basal insulin and GLP-1 receptor agonists but providing them in a single injection provides convenience and makes it easier for patients to comply. Additionally, these combination drugs are titrated based on fasting glucose values and therefore frequent home blood glucose monitoring is not required, which also makes compliance easier. In patients who do not have adequate control on basal insulin alone combination therapy can be a useful therapeutic option.

Coleselvam (Welchol) is a non-absorbed, polymeric, LDL cholesterol lowering and glucose lowering agent that is a high-capacity bile acid-binding molecule (215). This drug was developed primarily to lower LDL cholesterol levels and was later noted to have favorable effects on blood

BILE ACID SEQUESTRANTS

Introduction
glucose levels and was approved for improving glycemic control in patients with Type 2 diabetes (8,215). It should be noted that other bile acid sequestrants (cholestyramine) also have favorable effects on glycemic control (216).

Administration

The recommended dose of colesevelam is 6 tablets once daily or 3 tablets twice daily with meals (tabs 625 mg). Alternatively, one can take one 3.75-gram packet once daily mixed with water, fruit juice, or diet soft drinks and taken with meals or one flavored chewable bar (80 calories per bar) with meals. For patients with difficulty swallowing tablets the use of packets or chewable bars is recommended.

Mechanism of Action

The mechanism by which bile acid sequestrants improve glucose metabolism is not well understood and the literature on this topic is often contradictory (217,218). Colesevelam does not alter hepatic or peripheral insulin sensitivity or decrease glucose GI absorption (218,219). Neither acute nor chronic treatment affect post oral glucose tolerance test blood glucose levels (219). Additionally, colesevelam treatment did not alter endogenous glucose production, gluconeogenesis or glycogenolysis (218,219). Thus, the mechanisms accounting for the decrease in glucose effect of bile acid sequestrants remain unclear.

A leading hypothesis is that bile acid sequestrants improve glucose metabolism by stimulating the incretin pathway. Colesevelam increases GLP-1 and GIP concentrations suggesting that an increase in incretins contributes to the improvement in glycemic control (219-221). There are two pathways by which colesevelam increases GLP-1 secretion; (1) TGR5-mediated GLP-1 secretion in L cells and (2) intestinal proglucagon expression.

TGR5 is a G protein–coupled receptor expressed in many organs and tissues including the intestine (219,221). Bile acids activate TGR5 on the surface of intestinal L cells promoting GLP-1 secretion (219,221,222). Bile acid sequestrants appear to augment TGR5 activation and GLP-1 release, which occurs primarily in the distal intestine and colon (219,222,223).

FXR is a nuclear hormone receptor that complexes with RXR to alter the expression of a large number of genes (221). Bile acids are a ligand for FXR and activate FXR thereby regulating gene expression (221). FXR activation in intestinal L cells decreases proglucagon expression resulting in a decrease in GLP-1 production (224). Conversely, a decrease in bile acids due to binding to colesevelam increases GLP-1 gene expression and secretion in response to glucose improving glucose metabolism (224).

It is likely that there are both incretin dependent and independent mechanisms that account for the improvement in glycemic control with colesevelam treatment. The exact mechanisms by which bile acid sequestrants lower A1c levels remain to be elucidated.

Glycemic Efficacy

Colesevelam has modest effects on glycemic control, lowering A1c levels by approximately 0.5% when added to metformin, sulfonylureas, pioglitazone, or insulin (8,215,225). Colesevelam does not lead to an increase in weight (215). In combination with metformin hypoglycemia is not a problem but when used in combination with insulin or sulfonylureas hypoglycemia may occur (215).

Other Effects

LIPIDS

Colesevelam lowers LDL cholesterol levels by 15-20% and has only a modest effect on HDL cholesterol levels (215,226). The effect of bile acid sequestrants on triglyceride levels varies (226). In patients with normal triglyceride levels, bile acid sequestrants increase triglyceride levels by a small amount. However, as baseline triglyceride levels increase, the effect of bile acid sequestrants on plasma triglyceride levels becomes greater, and can result in substantial increases in triglyceride levels (226). In patients with triglycerides > 500mg/dl the use of bile acid sequestrants is contraindicated (226).

CARDIOVASCULAR DISEASE
There have been no randomized studies that have examined the effect of bile acid sequestrants on cardiovascular end points in subjects with diabetes. In non-diabetic subjects bile acid sequestrants have reduced cardiovascular events (227,228). Since bile acid sequestrants have a similar beneficial impact on serum lipid levels in diabetic and non-diabetic subjects one would anticipate that these drugs would also result in a reduction in events in the diabetic population.

Side Effects

Colesevelam does not have major systemic side effects as it is not absorbed and remains in the intestinal tract (226). However, it does cause gastrointestinal (GI) side effects (226). Constipation is a common side effect and can be severe. In addition, patients will often complain of bloating, dyspepsia, abdominal discomfort, and aggravation of hemorrhoids. Because of GI distress, a small number of patients will discontinue therapy with colesevelam. One can reduce or ameliorate these GI side effects by increasing hydration, adding fiber to the diet (psyllium), and using stool softeners.

Contraindications and Drug Interactions

Colesevelam treatment is contraindicated in patients with a history of bowel obstruction and is cautioned in those with a history of gastrointestinal motility disorders (i.e., gastroparesis) or gastrointestinal surgery (215,226). Colesevelam is contraindicated in patients with plasma triglyceride levels > 500 mg/dL or a history of hypertriglyceridemia-induced pancreatitis (package insert).

In the intestine bile acid sequestrants can impede the absorption of many other drugs (226). Colesevelam, which requires a much lower quantity of drug because of its high affinity and binding capacity for bile salts, has less of an effect on the absorption of other drugs than other bile acid sequestrants but can still adversely affect the absorption of certain drugs (Table 21) (226). Administration of these drugs, as well as vitamin supplements, 4 hours prior to administration of colesevelam minimizes pharmacokinetic interactions (226). This is particularly important with drugs that have a narrow toxic/therapeutic window, such as thyroid hormone, digoxin, or warfarin. It can be difficult for some patients, particularly those on multiple medications, to take colesevelam given the need to separate pill ingestion.

<table>
<thead>
<tr>
<th>Table 21. Drugs Affected by Colesevelam</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-thyroxine</td>
</tr>
<tr>
<td>Glyburide</td>
</tr>
<tr>
<td>Oral contraceptives</td>
</tr>
</tbody>
</table>

Colesevelam may also decrease the absorption of fat-soluble vitamins A, D, E, and K (package insert).

Summary

Colesevelam has the advantage of lowering both A1c and LDL cholesterol levels. However, the efficacy of lowering A1c and LDL cholesterol levels is modest compared to other drugs. Additionally, in our patients with diabetes who are often on multiple medications it can be difficult to coordinate taking colesevelam with these other medications.

<table>
<thead>
<tr>
<th>Table 22. Advantages and Disadvantages of Colesevelam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
</tr>
<tr>
<td>Lowers LDL cholesterol</td>
</tr>
<tr>
<td>No systemic effects</td>
</tr>
<tr>
<td>Once a day administration possible</td>
</tr>
<tr>
<td>No hypoglycemia</td>
</tr>
<tr>
<td>Weight neutral</td>
</tr>
</tbody>
</table>
Introduction

Pramlintide is a soluble synthetic analog of human amylin (229). Amylin is co-sequestered and co-secreted with insulin by the pancreatic beta cells in response to nutrient stimuli (229). Amylin secretion in response to nutrients is absent in type 1 diabetes and in patients with Type 2 diabetes there is impaired beta-cell secretion of amylin in response to nutrients (229). Amylin suppresses post-prandial arginine-stimulated glucagon secretion, suppresses appetite, and slows gastric emptying time through effects on the brain (229).

Administration

In patients with Type 2 diabetes initiate pramlintide at 60 ug subcutaneously immediately prior to each major meal. Increase the dose from 60 to 120 ug prior to each major meal when no clinically significant nausea has occurred for at least 3 days. Note the dose used to treat patients with Type 1 diabetes differs from the dose used in patients with Type 2 diabetes.

Mechanism of Action

Pramlintide attenuates post-prandial glucagon secretion, enhances satiety, and reduces food intake, which together improve glycemic control (229). These effects are mediated centrally (229).

Glycemic Efficacy

In a review of three randomized trials in patients with Type 2 diabetes comparing pramlintide vs. placebo the A1c was decreased by approximately 0.3-0.6% in the pramlintide group (230). Postprandial glucose excursions are significantly blunted with the addition of pramlintide (229). Pramlintide has only minimal effects on fasting glucose levels (230).

In a study comparing rapid acting insulin vs. pramlintide with meals a similar reduction in A1c was observed (231). In contrast, with rapid acting insulin, patients treated with pramlintide did not gain weight (231). Additionally, the frequency of hypoglycemia was less with pramlintide compared with rapid acting insulin (231).

Other Effects

Pramlintide treatment decreases weight (approximately 1-3 kg), which is likely due to decreased food intake (229,230). In a comparison of food intake during an ad libitum buffet meal, treatment with pramlintide resulted in an approximately 200 calorie decrease in food intake compared to placebo administration (232). Pramlintide also decreases gastric emptying (229).

Side Effects

A major side effect of pramlintide is nausea which can lead to patients discontinuing this drug (230).

Although pramlintide alone does not cause hypoglycemia, in combination with rapid acting meal time insulin the two drugs synergistically increase the risk of severe hypoglycemia (229). Therefore, rapid acting meal time insulin needs to be reduced upon initiation of pramlintide treatment to decrease the risk of hypoglycemia (229). Reducing rapid acting meal time insulin by 30-50% is recommended during the initial dose titration period (229).

Contraindications and Drug Interactions

Pramlintide is contraindicated in patients with hypoglycemia unawareness and confirmed gastroparesis (package insert).

Summary

Pramlintide is currently seldom used. Its modest effect on A1c levels coupled with the difficulties of administration (extra injections) and side effects has led to minimal use of this agent. Additionally, its major advantage of weight loss is now superseded by the use of GLP-1 receptor agonists.
### Table 23. Advantages and Disadvantages of Pramlintide

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight loss</td>
<td>Hypoglycemia</td>
</tr>
<tr>
<td>Decrease postprandial glucose</td>
<td>Frequent dosing</td>
</tr>
<tr>
<td></td>
<td>GI side effects</td>
</tr>
<tr>
<td></td>
<td>Expensive</td>
</tr>
<tr>
<td></td>
<td>Modest reduction in A1c</td>
</tr>
</tbody>
</table>

### SUMMARY

A large number of drugs are now available for lowering glucose levels. For information on the management of Type 2 diabetes and selecting amongst the available pharmacological agents see the chapter by Cavaiola and Pettus in Endotext (5). For information on the use of these drugs to treat diabetes during pregnancy, in children and adolescents, and for the prevention of diabetes see other Endotext chapters (2-4).

### ACKNOWLEDGEMENTS

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