Incretin-based therapies: can we achieve glycemic control and cardioprotection?

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Abstract
Glucagon-like (GLP-1) is a peptide hormone secreted from the small intestine in response to nutrient ingestion. GLP-1 stimulates insulin secretion in a glucose-dependent manner, inhibits glucagon secretion and gastric emptying, and reduces appetite. Because of the short circulating half-life of the native GLP-1, novel GLP-1 receptor (GLP-1R) agonists and analogs and dipeptidyl peptidase 4 (DPP-4) inhibitors have been developed to facilitate clinical use. Emerging evidence indicates that GLP-1-based therapies are safe and may provide cardiovascular (CV) benefits beyond glycemic control. Preclinical and clinical studies are providing increasing evidence that GLP-1 therapies may positively affect CV function and metabolism by salutary effects on CV risk factors as well as via direct cardioprotective actions. However, the mechanisms whereby the various classes of incretin-based therapies exert CV effects may be mechanistically distinct and may not necessarily lead to similar CV outcomes. In this review, we will discuss the potential mechanisms and current understanding of CV benefits of native GLP-1, GLP-1R agonists and analogs, and of DPP-4 inhibitor therapies as a means to compare their putative CV benefits.

Key Words
cardioprotection
dipeptidyl peptidase 4

Introduction
Despite significant advances in anti-glycemic therapies, cardiovascular disease (CVD) remains the major cause of morbidity and mortality in patients with type 2 diabetes mellitus (T2DM) (Fox et al. 2004, Booth et al. 2006, Perk et al. 2012). Moreover, certain classes of potent antidiabetic agents reduce microvascular complications but carry a increased risk of cardiovascular (CV) events (Nissen & Wolski 2007, Tzoulaki et al. 2009). At a time when T2DM constitutes a worldwide epidemic, there is a growing demand for new treatments that not only control plasma glucose but also reduce macrovascular complications.

Glucagon-like peptide 1 (GLP-1) is a peptide hormone synthesized in and secreted by enteroendocrine L cells in the gut and by the brainstem in the CNS. GLP-1 is secreted from the gut at low basal levels in the fasted state, peaking in response to nutrient ingestion, and leading to enhancement of glucose-stimulated insulin secretion, inhibition of glucagon secretion and gastric emptying, and reduction of appetite (Drucker 2006, Ussher & Drucker 2012). The native peptide (GLP-1 (7–36) amide) is rapidly cleavage by the dipeptidyl peptidase 4 (DPP-4) enzyme (Deacon et al. 1995), limiting circulating half-life and subsequent biological effects on pancreatic β cells. This pharmacokinetic response has led to the development of novel GLP-1 receptor (GLP-1R) agonists and analogs that are DPP-4-resistant and thus have a longer half-life. Similarly, DPP-4 inhibitors have also been developed that prolong the half-life of circulating native
GLP-1 (Fakhoury et al. 2010, Cernea & Raz 2011). All
classes of agents share the same insulinosotropic properties
and have been shown to have similar glucose-lowering
properties (Fineman et al. 2012). However, they vary with
respect to extra-pancreatic effects, including weight loss
and blood pressure (BP) control. Emerging evidence
indicates that GLP-1-based therapies are safe and may
provide CV benefits (Monami et al. 2011, Sun et al. 2012),
making this class of agents a particularly attractive option
for treating T2DM (Addison & Aguilar 2011).

Interestingly, the CV benefits of GLP-1 therapies
seems to be only partially mediated by their positive
action on glucose control in T2DM (Ussher & Drucker
2012). The mechanisms whereby this class of agents
mediates CV effects may be distinct, not necessarily
leading to similar outcomes. This review discusses the
potential mechanisms and current understanding of the
associated CV benefits of native GLP-1 (Barragan
et al. 1994, 1996) and its metabolites, GLP-1R agonists and
anals, and of DPP-4 inhibitor therapies (Table 1).

Improving glucose control: effect on CV
outcomes

GLP-1R activation stimulates adenylate cyclase, which
increases cAMP, leading to activation of protein kinase A
(PKA) and insulin biosyntheses by the β cells (Li et al. 2003).

GLP-1 stimulates insulin release in a KATP-mediated,
glucose-dependent fashion. GLP-1 also inhibits glucagon
secretion from pancreatic α cells, reducing hepatic glucose
production, further facilitating improvement in glycemic
control. Thus, the metabolic profile of GLP-1-based
therapies is broad and not restricted to its role as an
insulin secretagogue. Although results of studies examin-
ing the association between glycemic control with
alternative anti-diabetic agents and CV outcomes in
patients with T2DM have been inconsistent (Barragan
et al. 1996, Control et al. 2009, Ray et al. 2009), the broader
metabolic profile of GLP-1 may lead to beneficial effects
on CV outcomes not seen with the other anti-diabetic
agents (Ceriello 2006, Ussher & Drucker 2012, Herzlinger
& Horton 2013). As presented in Table 2, over 90 000
patients are currently enrolled in clinical studies designed
to assess the CV safety and efficacy of incretin-based
therapies and hopefully these will provide a better
understanding of the influence of GLP-1 in CVD (Scirica
et al. 2011, White et al. 2011, Sivertsen et al. 2012). Most of
new trials enrolled thousands of patients and are
adequately powered for safety and to show superiority
rather than non-inferiority. Recently, preliminary results
from the non-inferiority Vildagliptin in Ventricular
Dysfunction Diabetes (VIVIDD) trial were presented at
the Heart Failure Congress in Lisbon (McMurray 2013). In
this study, 254 patients with T2DM and New York Heart

<table>
<thead>
<tr>
<th>Administration</th>
<th>Native GLP-1 (7–36)</th>
<th>GLP-1 analogs and agonists</th>
<th>DPP-4 inhibitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infusion/injection</td>
<td>Pharmacological</td>
<td>No</td>
<td>Oral</td>
</tr>
<tr>
<td>GLP-1 level</td>
<td>GLP-1 receptor and metabolites</td>
<td>Yes</td>
<td>Physiological</td>
</tr>
<tr>
<td>DPP-4-resistant</td>
<td>GLP-1 receptor</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mechanism of action</td>
<td>GLP-1 receptor</td>
<td>GLP-1 receptor receptor, SDF1α, BNP, decrease cytokines</td>
<td></td>
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<tr>
<td>Metabolic actions</td>
<td>Improved</td>
<td>Improved</td>
<td>Improved</td>
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<td>FPG</td>
<td>Improved</td>
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<td>PPG</td>
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<td>Glucagon</td>
<td>Reduced</td>
<td>Reduced</td>
<td>Reduced</td>
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<tr>
<td>Insulin sensitivity</td>
<td>Enhanced/neutral</td>
<td>Improved</td>
<td>Unknown</td>
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<td>Lipid profile</td>
<td>Improved</td>
<td>Improved</td>
<td>Improved</td>
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<td>Weight effects</td>
<td>Loss</td>
<td>Loss</td>
<td>Neutral</td>
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<tr>
<td>Cardiovascular actions</td>
<td>Unmodified</td>
<td>Unmodified/increased</td>
<td>?</td>
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<tr>
<td>Heart ratea</td>
<td>Reduced</td>
<td>Reduced</td>
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<td>Blood pressurea</td>
<td>Present</td>
<td>Present</td>
<td>Present</td>
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<td>Cardioprotection</td>
<td>Improved</td>
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<td>Improved</td>
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<td>Cardiac function</td>
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FPG, fasting plasma glucose; PPG, postprandial plasma glucose; BNP, brain natriuretic peptide; CV, cardiovascular; DPP-4, dipeptidyl peptidase 4; GLP-1, glucagon-like peptide 1; NA, not applicable; SDF1α, stromal cell-derived factor-1α; ?, Uncertain/not known or definite. *Clinical studies.
Table 2  Ongoing cardiovascular outcome studies in patients with type 2 diabetes mellitus

<table>
<thead>
<tr>
<th>Agent (clinical study)</th>
<th>Identification number (Clinical-Trials.gov)</th>
<th>Estimated primary completion date</th>
<th>Primary outcome measures</th>
<th>Time frame</th>
<th>Study design</th>
<th>Intervention</th>
<th>Estimated enrollment</th>
<th>HbA1c (%)</th>
<th>Treatment regimen</th>
<th>Age (years)</th>
<th>CV history</th>
</tr>
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<tr>
<td>GLP-1R agonists and analogs</td>
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<tr>
<td>Exenatide (EXSCEL) (Gaebler et al. 2012)</td>
<td>NCT01144338</td>
<td>03/2017</td>
<td>Composite (CV death, MI, or stroke)</td>
<td>5.5 years</td>
<td>R, S/E, PA, DB, phase 3</td>
<td>2 mg s.c. weekly</td>
<td>9500</td>
<td>6.6–10.0</td>
<td>OAD mono or combination therapy&lt;sup&gt;b&lt;/sup&gt; ± Insulin</td>
<td>≥ 18</td>
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<tr>
<td>Dulaglutide (REWIND)</td>
<td>NCT01394952</td>
<td>04/2019</td>
<td>Composite (CV death, MI, or stroke)</td>
<td>6.5 years</td>
<td>R, S/E, PA, DB, phase 3</td>
<td>1.5 mg s.c. weekly</td>
<td>9622</td>
<td>≤ 9.5</td>
<td>Treatment naïve, or OAD mono or combination therapy&lt;sup&gt;b&lt;/sup&gt; ± Insulin</td>
<td>≥ 50</td>
<td>CV, cerebrovascular or peripheral vascular disease or CRF or CHF or ≥60 years with ≥2 CV risk factors</td>
</tr>
<tr>
<td>Liraglutide (LEADER)</td>
<td>NCT01179048</td>
<td>01/2016</td>
<td>Composite (CV death, MI, or stroke)</td>
<td>60 months</td>
<td>R, S/E, PA, DB, phase 3</td>
<td>Maximum dose of 1.8 mg s.c. daily</td>
<td>9340</td>
<td>≥ 7</td>
<td>Treatment naïve, or OAD mono or combination therapy&lt;sup&gt;b&lt;/sup&gt; ± Insulin</td>
<td>≥ 50</td>
<td>CV, cerebrovascular or peripheral vascular disease or CRF or CHF or ≥60 years with CV risk factors</td>
</tr>
<tr>
<td>Lixisenatide (ELIXA)</td>
<td>NCT01147250</td>
<td>09/2014</td>
<td>Composite (CV death, MI, or unstable angina)</td>
<td>203 weeks</td>
<td>R, E, PA, DB, phase 3</td>
<td>20 µg s.c. daily</td>
<td>6000</td>
<td>5.5–11</td>
<td>Treatment naïve, or OAD mono or combination therapy&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≥ 30</td>
<td>ACS last 180 days</td>
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<td>DPP-4 inhibitors</td>
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<tr>
<td>Alogliptin (EXAMINE) (White et al. 2011)</td>
<td>NCT00968708</td>
<td>05/2013</td>
<td>Composite (CV death, MI, stroke, or unstable angina)</td>
<td>4.75 years</td>
<td>R, S, PA, DB, phase 3</td>
<td>12.5 mg oral daily</td>
<td>5389</td>
<td>6.5–11</td>
<td>OAD mono or combination therapy&lt;sup&gt;b&lt;/sup&gt; ± Insulin</td>
<td>≥ 18</td>
<td>ACS before 15–90 days</td>
</tr>
<tr>
<td>Linagliptin (CAROLINA)</td>
<td>NCT01243424</td>
<td>09/2018</td>
<td>Composite (CV death, MI, stroke, or unstable angina)</td>
<td>400 weeks</td>
<td>R, S/E, PA, DB, phase 3</td>
<td>5 mg OAD</td>
<td>6000</td>
<td>6.5–8.5</td>
<td>Treatment naïve, or mono/dual therapy with metformin and/or an α-glucosidase inhibitor&lt;sup&gt;b&lt;/sup&gt;</td>
<td>40–85</td>
<td>CV or diabetes end-organ damage or ≥70 with ≥2 CV risk factors</td>
</tr>
<tr>
<td>Saxagliptin (SAVOR-TIMI53) (Scirica et al. 2011)</td>
<td>NCT01107886</td>
<td>07/2013</td>
<td>Composite (CV death, MI, stroke, or unstable angina)</td>
<td>4 years</td>
<td>R, E, PA, DB, phase 4</td>
<td>5 mg or 2.5 g oral daily</td>
<td>16 500</td>
<td>≥ 6.5</td>
<td>Treatment naïve, or anti-diabetic treatment/insulin&lt;sup&gt;b&lt;/sup&gt;</td>
<td>≥ 40</td>
<td>CV disease and/or multiple risk factors</td>
</tr>
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</table>
Table 2 Continued

<table>
<thead>
<tr>
<th>Eligibility criteria</th>
<th>Estimated primary completion date</th>
<th>Primary outcome measures</th>
<th>Time frame</th>
<th>Study design</th>
<th>Intervention</th>
<th>Estimated enrollment</th>
<th>Study agent</th>
<th>Study identifier (ClinicalTrials.gov)</th>
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<tr>
<td></td>
<td>12/2014</td>
<td>Composite (CV death, M. stroke, unstable angina)</td>
<td>5 years</td>
<td>R, S, PA, DB, phase 3</td>
<td>50 or 100 mg oral daily</td>
<td>14 000</td>
<td>Sitagliptin (TECOS)</td>
<td>NCT00790205</td>
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**Incretins and CV effects of weight loss**

GLP-1R activation in the hypothalamus reduces appetite and promotes satiety by inhibition of gastric emptying, leading to weight loss (Flint et al. 1998, Larsen et al. 2001). In patients with T2DM, the use of exenatide (Amori et al. 2007) and liraglutide (Vilsboll 2007) has been associated with significant weight loss. Similar results were confirmed in a study with non-diabetic, obese patients treated with liraglutide (Astrup et al. 2012). The weight-reducing effect of GLP-1 contributes to beneficial effect on CV risk factors such as lipid profile and BP (Flint et al. 1998, Larsen et al. 2001, Kenchaiah et al. 2002, Shibata et al. 2005, Horton et al. 2010) in addition to glycemic control. In experimental animal models, reduction of body weight in spontaneously hypertensive and heart failure-prone rats treated with native GLP-1 was seen in association with improvement of LV function, systemic metabolic parameters, and survival (Poomima et al. 2008). Similarly, a 5-week infusion of native GLP1 was associated with ~5 kg weight reduction in patients with class III/IV NYHA heart failure (Sokos et al. 2006). Clinical trials with GLP-1 agonists and analogs in patients with T2DM have demonstrated reductions in BP in parallel with reductions in body weight (Varanasi et al. 2012). The extent to which weight reduction leads to BP reduction is difficult to discriminate in these clinical trials but underscores the fact that GLP-1 may have several and perhaps synergistic mechanisms of action to favorably influence the metabolic profile.

**CV effects of GLP-1 and GLP-1R agonists and analogs**

The human GLP-1R is a class B G-protein-coupled receptor expressed not only on pancreatic islet α and β cells but also in the heart (Fig. 1A and B), kidney, brain, blood vessels,
endothelial cells, and gastrointestinal tract (Bullock et al. 1996, Ban et al. 2008). Preclinical and clinical studies have elucidated some of the biological actions of the GLP-1R system on the heart and blood vessels independent of its actions on pancreatic islets and the subsequent improvement in glycemic control (Barragan et al. 1994, Zhao et al. 2006, Green et al. 2008).

Effects on heart rate and BP

The mechanisms leading to reduced BP and changes in heart rate (HR) are not fully understood, but GLP-1’s effects on BP and HR appear to be both species- (rodents vs other mammals) and preparation-specific (anesthetized vs conscious, isolated vs intact cardiac preparations) with differing effects depending on the duration of the GLP-1R activation and preexistence of comorbitides. Preclinical studies with GLP-1 analogs indicate that reduction in BP could be dependent on the autonomic nervous system (Bharucha et al. 2008), while a recent study indicates that GLP-1R activation promotes the secretion of atrial natriuretic peptide (ANP) and that a GLP-1R-dependent and ANP-dependent axis regulates BP (Kim et al. 2013). Similarly, both autonomic nervous system-dependent and -independent mechanisms have been suggested to lead to rises in HR (Gardiner et al. 2008).

Acute administration of GLP-1 and exendin-4 in rats increased BP and HR (Barragan et al. 1996), while a 7-day infusion of exendin-4 resulted in reduction of BP in a rat model (Laugero et al. 2009). In healthy human subjects, infusion of native GLP-1 for 65 min had no effect on BP or on HR variability (Bharucha et al. 2008), while 48-h infusion in 15 non-diabetic patients with heart failure (NYHA class II/III) resulted in small increase in HR and diastolic BP (Halbirk et al. 2010). In contrast, in a 5-week infusion of native GLP-1 in 12 heart failure patients (NYHA class III/IV), there were no significant changes in the HR or BP, although the systemic vascular resistance was significantly lower in the treated group (Sokos et al. 2006). Thus, even in humans with heart failure, the effects of native GLP-1 on HR and BP vary with respect to severity of heart failure and duration of GLP-1 exposure.

The body of evidence examining the effects of GLP-1 agonists and analogs is more robust in patients with T2DM. A significant reduction in systolic BP was demonstrated after a 52-week treatment with exenatide in a randomized trial with T2DM patients (Buse et al. 2010). Similar results confirm the reduction in BP with exenatide therapy in a large retrospective analysis of patients with T2DM (Horton et al. 2010). Moreover, a

Figure 1
GLP-1R expression in mouse hearts. (A) Hearts labeled with anti-sarcomeric α-actinin (red), anti-GLP-1R (green), and Hoechst nuclear stain (blue) revealed GLP-1R expression on cardiomyocytes, (B) endocardium (arrowheads), (C) vascular endothelium, and smooth muscle cells (SMCs) (arrowheads and arrows respectively). (C) and 30 μmol/l (A and B). Modified, with permission, from Ban K, Noyan-Ashraf MH, Hoefer J, Bolz SS, Drucker DJ & Husain M 2008 Cardioprotective and vasodilatory actions of glucagon-like peptide 1 receptor are mediated through both glucagon-like peptide 1 receptor-dependent and -independent pathways. Circulation 117 2340–2350.
meta-analysis including 31 trials evaluating the effects of exenatide and liraglutide on BP confirmed a reduction in systolic pressure by \(-1.79\) mmHg (\(-2.94\) to \(-0.64\)) and \(-2.39\) mmHg (\(-3.35\) to \(-1.42\)) compared with placebo and active anti-diabetic drug therapy respectively (Robinson et al. 2013). Whether changes in BP were a consequence of the concomitant reduction in body weight remains to be determined definitively. In keeping with a direct anti-hypertensive effects is the finding that liraglutide significantly reduced systolic in T2DM (Gallwitz et al. 2010, Varanasi et al. 2012), before the significant weight loss was observed (Gallwitz et al. 2010).

In addition, small increases in HR have been reported in several clinical studies and recently compiled in a meta-analysis including 22 trials (Matte et al. 2009, Pratley et al. 2010, Buse et al. 2011, Nathanson et al. 2012, Robinson et al. 2013). GLP-1 agonists lead to an increase in HR of 1.86 beats/min (bpm; 0.85–2.87) and 1.9 bpm (1.30–2.50) compared with placebo and active control respectively. HR rises were more evident for liraglutide than exenatide, and for exenatide long-acting release than exenatide twice daily (Robinson et al. 2013). The clinical relevance of those findings is still not fully understood and may be clarified by the ongoing CV safety trials (Table 2).

Cardioprotective effects

The cardioprotective effects of GLP-1 and GLP-1R agonists and analogs in ischemic heart disease have been supported by extensive studies of rodent models of ischemia–reperfusion using isolated heart preparations (Bose et al. 2005a, Nikolaidis et al. 2005a, Zhao et al. 2006, Noyan-Ashraf et al. 2009, Timmers et al. 2009). The cardioprotective effects seem to be related to the elevation of intracellular calcium by a cAMP-activated PKA pathway (Xiao et al. 2011) and the anti-apoptotic signaling and inhibition of mitochondrial permeability transition pore opening by the activation of the pro-survival reperfusion injury salvage kinase pathway (Hausenloy & Yellon 2004, 2007). Indeed, GLP-1 (Nikolaidis et al. 2005a, Xiao et al. 2011), exendin-4 (Fineman et al. 2012), exenatide (Timmers et al. 2009), albiglutide (Bao et al. 2011), GLP-1-transferrin (Matsubara et al. 2011), and liraglutide (Noyan-Ashraf et al. 2009) improved post-ischemic contractile dysfunction and decreased infarct size in different in vivo animal models of ischemia and reperfusion. In a porcine model of ischemia–reperfusion, exenatide reduced infarct size by 40% and prevented further deterioration of systolic and diastolic function (Timmers et al. 2009). These findings were associated with reduced apoptosis and nuclear oxidative stress and improvement in myocardial glucose metabolism (Timmers et al. 2009). Moreover, GLP-1 administered to conscious dogs undergoing a 10-min coronary occlusion followed by 24 h of reperfusion enhanced recovery from myocardium stunning as demonstrated by the earlier and complete recovery of the regional wall motion in the treated animals (Fig. 2; Nikolaidis et al. 2005a). In addition, GLP-1 was associated with improvement in myocardium glucose uptake and isovolumic LV relaxation (Barragan et al. 1994).

It is worth of note that, positive findings are not universal as other animal studies were not able to demonstrate similar results (Kavianipour et al. 2003, Kristensen et al. 2009). In a porcine model of ischemia–reperfusion, recombinant GLP-1 infusion improved myocardial glucose utilization but had no beneficial effects on infarct size or cardiac function (Kavianipour et al. 2003). Similarly, despite being associated with higher HR, treatment with liraglutide had neutral effects on infarct size and hemodynamics in a porcine model of ischemia–reperfusion (Kristensen et al. 2009). These inconsistent results may be related to different doses, timing of administration, agents employed, and animal models.

Figure 2

Regional post-ischemic contractile function recovery with GLP-1 in a canine model. Regional wall thickening responses to coronary artery occlusion and coronary artery reperfusion in a canine model. The differences in patterns of recovery of regional contractile function between the control (solid line) and GLP-1-treated animals (dotted lines) are illustrated by the significant dissociation between normalization of coronary flow and recovery of the respective posterior wall thickness, in the control group, consistent with myocardial stunning, even 24 h post-coronary artery reperfusion. In contrast, GLP-1-treated dogs demonstrated rapid and complete recovery of regional function in the ischemic zone over time. *P<0.01 vs baseline ***P<0.001 vs control by ANOVA. CAO, coronary artery occlusion; CAR, coronary artery reperfusion. Modified, with permission, from Nikolaidis LA, Kristensen K, Buse K et al. Glucagon-like peptide-1 limits myocardial stunning following brief coronary occlusion and reperfusion in conscious canines. Journal of Pharmacology and Experimental Therapeutics 312 303–308.

http://joe.endocrinology-journals.org
DOI: 10.1530/JOE-13-0195
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used, highlighting the need for further investigation, particularly in large-animal models.

Positive effects of native GLP-1 infusion in patients with acute myocardial infarction (MI) and LV dysfunction after successful reperfusion were demonstrated in a non-randomized pilot study \((n=21; \text{Nikolaidis et al. 2004b})\). In this study, 72-h infusion with GLP-1 significantly improved LVEF \((29 \pm 2–39 \pm 2\% ; P<0.01)\), and wall motion score indices \((1.94 \pm 0.11–1.63 \pm 0.09 ; P<0.01)\) compared with control \((\text{Fig. 3A and B respectively; Nikolaidis et al. 2004b})\). Furthermore, GLP-1 treatment was associated with significant reduction in hospital length-of-stay \((6.1 \pm 1.3 \text{ vs } 9.8 \pm 1.5 \text{ days}; P<0.02)\) and in-hospital mortality \((10 \text{ vs } 27\% ; \text{Nikolaidis et al. 2004b})\).

Supporting those results, native GLP-1 infusion reduced improvement in the GLP-1-treated patients compared with the control group. Modified, with permission, from Nikolaidis LA, Mankad S, Sokos GG, Miske G, Shah A, Elahi D & Shannon RP 2004. Published by Bioscientifica Ltd

Effects of GLP-1 infusion on cardiac function in patients with acute myocardial infarction and left ventricular dysfunction. (A) Changes in LVEF after 72 h of rGLP-1 infusion (white bars) vs control subjects (black bars). (B) Changes in regional wall motion score at the per-infarct zone in rGLP-1-treated patients vs control subjects. Results indicate left ventricular function improvement in the GLP-1-treated patients compared with the control group. Modified, with permission, from Nikolaidis LA, Mankad S, Sokos GG, Miske G, Shah A, Elahi D & Shannon RP 2004b Effects of glucagon-like peptide-1 in patients with acute myocardial infarction and left ventricular dysfunction after successful reperfusion. Circulation 109 962–965.

Impact on cardiac function

Activation of GLP-1R has been associated with improvements in CV function in heart failure in preclinical \((\text{Nikolaidis et al. 2004a, Ceriello 2006, Bhashyam et al. 2010, Liu et al. 2010})\) and clinical settings \((\text{Sokos et al. 2006, Vilsholl 2007, Lonborg et al. 2012a})\). In a conscious, canine model of LV systolic dysfunction induced by rapid pacing, activation of p38 MAPK and nitric oxide (NO) synthase and an increase in GLUT1 expression led to an insulin-independent increase in myocardial glucose uptake, indicating a non-insulin-mediated mechanisms for CV benefits of GLP-1 \((\text{Bhashyam et al. 2010})\).

The beneficial effects of GLP-1 in the failing heart were also demonstrated in clinical settings. GLP-1 infusion for 5 weeks added to standard therapy in patients with and without diabetes and NYHA class III/IV heart failure led to improvement in LV systolic function, and exercise tolerance, as well as the 6-min walk distance, and quality of life. No changes were observed in the control group \((\text{Table 3; Sokos et al. 2006})\). Indeed, GLP-1 was also demonstrated to have potential to improve myocardial glucose metabolism and cardiac function in patients with heart failure and DM \((\text{Thrainsdottir et al. 2004})\). Interestingly, in a randomized, double-blind, crossover trial of 20 non-diabetic patients with HF NYHA class II/III, short-
Table 3  Safety and efficacy of sustained GLP-1 infusion in with advanced heart failure. GLP-1 infusion in patients with advanced systolic hear failure (NYHA class III–IV), including both diabetics and non-diabetics, was associated with improvement in LVEF, exercise tolerance, and quality of life.

<table>
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<tr>
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<th>GLP-1 patients (n = 12)</th>
<th>Control patients (n = 9)</th>
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<tr>
<td>LVEF (%) Baseline</td>
<td>21 ± 3</td>
<td>21 ± 4</td>
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<tr>
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<td>5 weeks</td>
<td>5 weeks</td>
</tr>
<tr>
<td>VO2 max</td>
<td>10.8 ± 0.9</td>
<td>13.9 ± 0.6*</td>
</tr>
<tr>
<td></td>
<td>6 weeks</td>
<td>13.3 ± 0.9</td>
</tr>
<tr>
<td>6-min walk (m)</td>
<td>232 ± 15</td>
<td>286 ± 12*</td>
</tr>
<tr>
<td></td>
<td>10 weeks</td>
<td>233 ± 21</td>
</tr>
<tr>
<td>Minn QOL</td>
<td>64 ± 4</td>
<td>44 ± 5*</td>
</tr>
<tr>
<td></td>
<td>12 weeks</td>
<td>52 ± 12</td>
</tr>
<tr>
<td>BNP (pg/ml)</td>
<td>289 ± 90</td>
<td>218 ± 102</td>
</tr>
<tr>
<td></td>
<td>20 weeks</td>
<td>296 ± 129</td>
</tr>
</tbody>
</table>

*P < 0.001 vs baseline. LVEF, left ventricular systolic function; VO2 max, maximal oxygen consumption; 6-min walk, 6-min walk distance test; Minn QOL, Minnesota Living with Heart Failure Quality of Life Score; BNP, brain natriuretic peptide. Reproduced, with permission, from Sokos GG, Nikolaidis LA, Mankad S, Elahi D & Shannon RP 2006 Glucagon-like peptide-1 infusion improves left ventricular ejection fraction and functional status in patients with chronic heart failure. *Journal of Cardiac Failure* 12 694–699.

of ischemia–reperfusion injury was present even in the absence of functional GLP-1R. The authors proposed a NO/cGMP-dependent cardioprotecive mechanism, supported by the finding of increased expression of cGMP and absence of effects upon NO synthase inhibition (Ban et al. 2008). In line with those results, a 48-h infusion of GLP-1 (9–36) in a model of pacing-induced heart failure in conscious dogs improved LV function, reduced systemic vascular resistance, and increased myocardial glucose uptake (Nikolaidis et al. 2005b) independent of the action of insulin. Functional improvements seen with continuous infusion of GLP-1 (9–36) paralleled the results using native GLP-1 in the same animal model, indicating that GLP-1 metabolites may play a key role in this setting (Nikolaidis et al. 2005b, Bhashyam et al. 2010; Fig. 4A, B, C and D). Although the data are promising, further studies are necessary to further elucidate the role of the GLP-1 metabolites as therapeutic agents in CVD. The work has considerable implications for use of these agents beyond glycemic control.

**CV effects of DPP-4 inhibitors**

DPP-4 is the first step in the breakdown of native GLP-1 (7–36) amide. Inhibition of DPP-4 became an attractive therapeutic target as such agents would prolong the circulating half-life of native GLP-1 (7–36) and prolong its insulinotropic effects. However, DPP-4 cleaves multiple peptides, many of which have demonstrated to have CV actions (Fig. 5; Drucker & Nauck 2006, Ussher & Drucker 2012), although prolonged circulating GLP-1 levels may be important in many of those actions, the circulating concentrations achieved in the plasma are threefold to fourfold lower than those with pharmacological doses of GLP-1R agonist or analogs.

Thus, attention has focused on other DPP-4 substrates that have recognized CV benefits. B-type (brain) natriuretic peptide 1–32 (BNP 1–32) is a peptide secreted by the ventricle and a key factor in regulating body fluid homeostasis and vascular tone (Ogawa et al. 1996, Boerrigter et al. 2007). Therefore, cleavage by DPP-4 leads to a reduction of diuretic and natriuretic actions and inhibition of vasodilatation (Boerrigter et al. 2007). Additionally, BNP seems to reduce cardiac remodeling after acute myocardial infarction (Moilanen et al. 2011, Palazzuoli et al. 2011), which could be another potential benefit of using DPP-4 inhibitors (DPP-4i). Although cardioprotection of BNP via DPP-4 inhibition was demonstrated in a porcine model of heart failure (Gomez et al. 2012), further studies are needed to clarify those interactions.
Stromal cell-derived factor-1α (SDF1α) is a chemokine that promotes homing of endothelial progenitor cells to sites of injury and therefore promotes neoangiogenesis (Asahara et al. 1997). Because SDF1α is cleaved by DPP-4, DPP-4 inhibition increases levels of circulating SDF1α. As a result, sitagliptin increased levels of circulating endothelial progenitor cells in T2DM patients (Fadini et al. 2010), while diprotin A in association with granulocyte colony-stimulating factor decreased infarct size and enhanced neovascularization, LVEF, and survival in a rodent model of MI (Zaruba et al. 2009). Besides the potential beneficial actions of BNP and SDF1α, other DPP-4 substrates may also have CV effects. Thus, while DPP-4 inhibition and GLP-1 analogs may have similar CV profiles, they may be achieved through differing mechanisms.

**Effects on BP**

Sitagliptin reduced blood pressure in a rodent model of metabolic syndrome (Ferreira et al. 2010). Discrepant results were found in a spontaneously hypertensive rat model, with benefit only observed in the young animals (5 vs 20 weeks old; Pacheco et al. 2011). Nevertheless, small clinical studies in non-diabetic (Mistry et al. 2008) and diabetic (Ogawa et al. 2011) hypertensive patients treated with sitagliptin identified an association with reduction of BP in the absence of weight loss. Similar results were also observed in larger studies in T2DM patients (Bergenstal et al. 2010, Russell-Jones et al. 2012). Notably, these effects on BP occur in the absence of significant weight loss.

**DPP-4 inhibition in ischemic heart disease**

DPP-4 inhibitors probably share some GLP-1R-dependent cardioprotective mechanisms previously described (Ogawa et al. 2011), although it should be noted that DPP-4 inhibitors yield physiological not pharmacological levels of circulating GLP-1. Indeed, preclinical studies demonstrate cardioprotection associated with DPP4-1 therapy in *in vivo* models (Ye et al. 2010, Huisamen et al. 2011).
Moreover, data indicates that enhanced angiogenesis may also play a role in the cardioprotection as demonstrated by a study addressing the adjunctive affect of SDF1α (Zaruba et al. 2009). In clinical settings, the DPP-4i sitagliptin improved global cardiac performance and attenuated post-ischemic stunning in 14 patients with coronary artery disease during dobutamine stress echocardiography (Read et al. 2010). More recently, the preliminary results of the TIMI 53/Savor trial with saxagliptin indicate that while safe, this DPP-4i did not reduce composite CV events of CV death, MI, or stroke. The complete results of the study will be released shortly.

**Role of DPP-4 inhibition in cardiac function**

Few preclinical studies have directly addressed the role of DPP-4 inhibition in heart failure models. Sitagliptin increased stroke volume and reduced HR in a porcine model of pacing-induced heart failure (Gomez et al. 2012). On the other hand, vildagliptin had neutral effects on cardiac function in a rat model of ischemic cardiomyopathy (Yin et al. 2011). As previously described, the first clinical trial looking into CV effects of vildagliptin in patients with diabetes and NYHA class I–III (n=254) confirmed the neutral effects in cardiac function measured by the mean increase in EF in the treatment group compared with the control group (4.1 vs 3.5% respectively, \(P=0.67\)) and raised safety concerns related to a potential negative effect on LV compliance and an increase in non-cardiac mortality (McMurray 2013). Taken together, these early data indicate that the CV profile of DPP-4 inhibitors may vary from the CV profile of the native GLP-1 peptide and GLP-1R agonists and analogs.

**Summary**

Incretin-based therapies have emerged as potent anti-diabetic agents of particular clinical interest due to the emerging evidence that they are associated with CV benefits. Currently, over 120 000 patients are enrolled in CV outcome trials with incretin-based therapies designed to demonstrate safety and efficacy. Specifically, most of these trials have primary major adverse cardiac event (MACE) outcomes of CV death, MI, or need for revascularization. As such, we stand on the verge of learning a great deal about the ability of incretin-based therapies to improve CV outcomes in T2DM. Nonetheless, much remains to be learned with respect to this promising class of agents. First, it is not certain whether this is a class effect or whether there are differences between types of incretin-based therapies (native peptide vs GLP-1 long-acting analogs vs DPP-4 inhibitors). A related question bears on whether the metabolites contribute...
to CV benefits. Secondly, it is unclear whether incretin-based therapies have CV benefits that extend beyond T2DM. Finally, the use of incretin-based therapies as metabolic modulators in heart failure represents a new therapeutic approach in this important CV domain. Time and careful study will tell whether these agents will establish a new therapeutic paradigm.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review reported.

Funding
Dr R P S is the founder of Ventrigen, LLC, and has received research support from Pfizer and Astra Zeneca/Bristol Myers Squibb for the study of incretins and DPP-4 inhibitors in CV disease states in animals. No industry-based products or support were provided for these studies. Dr R P S holds USA Patent 7,182,822, the use of GLP-1 for the treatment of LV systolic dysfunction, and USA provisional patent 6/151390 entitled the Methods and Compositions for Inhibiting Delayed Graft Function. Dr F S A holds a USA provisional patent 13/809,154 entitled Use of Interleukin-15 to treat Cardiovascular Diseases.

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**Journal of Endocrinology**

**Thematic Review**

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**Incretin-based therapies and cardioprotection**

221:1  T28


Received in final form 15 July 2013
Accepted 5 August 2013
Accepted Preprint published online 7 August 2013