A SURPRISINGLY POOR CORRELATION BETWEEN IN VITRO AND IN VIVO TESTING OF BIOMATERIALS FOR BONE REGENERATION: RESULTS OF A MULTICENTRE ANALYSIS

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Abstract

New regenerative materials and approaches need to be assessed through reliable and comparable methods for rapid translation to the clinic. There is a considerable need for proven in vitro assays that are able to reduce the burden on animal testing, by allowing assessment of biomaterial utility predictive of the results currently obtained through in vivo studies. The purpose of this multicentre review was to investigate the correlation between existing in vitro results with in vivo outcomes observed for a range of biomaterials. Members from the European consortium BioDesign, comprising 8 universities in a European multicentre study, provided data from 36 in vivo studies and 47 in vitro assays testing 93 different biomaterials. The outcomes of the in vitro and in vivo experiments were scored according to commonly recognised measures of success relevant to each experiment. The correlation of in vitro with in vivo scores for each assay alone and in combination was assessed. A surprisingly poor correlation between in vitro and in vivo assessments of biomaterials was revealed indicating a clear need for further development of relevant in vitro assays. There was no significant overall correlation between in vitro and in vivo outcome. The mean in vitro scores revealed a trend of covariance to in vivo score with 58 %. The inadequacies of the current in vitro assessments highlighted here further stress the need for the development of novel approaches to in vitro biomaterial testing and validated pre-clinical pipelines.

Keywords: in vivo, in vitro, correlation, biomaterials, multicentre study.

Introduction

Researchers and key decision-makers have enthusiastically endorsed the therapeutic promise of regenerative medicine. The anticipated clinical impact has led to considerable research investment and a resultant proliferation of regenerative medicine-related innovations and technologies. One of the most mature research areas in this field is the development of innovative biomaterials for bone regeneration.

Over the last decade, a plethora of increasingly advanced biomaterials, designed to provide specific mechanical or morphological properties and kinetics combined with an expansive range of biomimetic modifications have been developed for use (in isolation or in combination with cell therapy) in bone regeneration (Billstrom et al., 2013; Garcia-Gareta et al., 2015; Gibbs et al., 2014). However, the range of materials and resultant potential therapies present a significant burden for pre-clinical in vivo testing and subsequent clinical translation. The challenge for
regenerative medicine is analogous to that faced in toxicity testing where the escalating number of new chemical entities (NCEs) and the extensive requirement for animal testing had the result that only a fraction of NCEs were considered for further evaluation. As with NCE toxicity testing, moving away from the use of, or at least reducing, animal testing is a critical imperative in regenerative medicine.

Both ethical and efficiency concerns underlie this imperative. Animal behaviour and neurophysiology appears increasingly to validate the sentiments (not the methods) of the animal rights movement. For example, a study by Bartal et al. showed pro-social behaviour in rats (Bartal et al., 2011) and a special vocalisation of adolescent rats is proposed to have an evolutionary relation to the joyfulness of children’s laughter (Bering 2012; Panksepp and Burgdorf, 2003). In response to this increasing awareness Russell and Burch’s 3Rs initiative is being implemented legislatively and adopted by funders and governments to enable: (1) reduction of the number of animals used, (2) refinement of experiments to minimise animal suffering and distress and (3) replacement of animal testing by alternative in vitro approaches (Russell and Burch, 1959).

The extensive fiscal and time expenditure of animal experimentation has provided a further significant driver behind the development for an increased reliance on relatively high throughput in vitro alternatives to animal testing. In a systematic review, Morgan et al. compared cost estimates of drug developments and observed the cost estimates of preclinical work ranged from USD$ 46 to USD$ 165 billion (Morgan et al., 2011). To date, there remains no gold standard for the estimation of the costs spanning from developing a drug through to clinical implementation.

Successful replacement and reduction of animal procedures has been achieved in various fields, as indicated above and perhaps most notably in toxicology testing, through improvements to in vitro and in silico models (Langley et al., 2007; Vodovotz et al., 2006) as well as improvements in sharing of existing data in order to inform new studies (Knight, 2008). The same development is necessary in the field of regenerative materials, which needs to be evaluated with reliable and comparable methods. One possibility is to draw conclusions from previously performed experiments/studies through a direct correlation of in vitro versus in vivo outcomes of biomaterials. Are there parameters that have been measured within in vitro assays that correlate with objective in vivo outcomes?

It is important to note in vitro and in vivo evaluations will likely both remain critically important in the development of a clinical therapeutic entity. In vivo experiments allow rigorous assessment of the material-cell/host interaction and the regenerative efficacy of a biomaterial strategy. The wide range of parameters provided through in vivo assessment are important for osteo-regenerative materials, as bone itself is a complex organ responsible for protection, muscle attachment, calcium homeostasis and as a centre of haematopoiesis. Bone is a highly organised structure that constantly remodelled and optimised to allow mechanical loading and to meet the demand for calcium by a strictly controlled interplay between osteoblasts and osteoclasts, conducted by osteocytes (Bonewald 2006; Bonewald 2011; Frost 1994). If a defect is not too large, bone has an inherent ability to regenerate completely without scar-formation. This self-regeneration is orchestrated by a number of cytokines and involves a variety of cells where the immune system plays an important part (Marsell and Einhorn 2009; Marsell and Einhorn 2011). Bone regeneration needs certain conditions, where vascularisation, stabilisation, scaffolding, cell signalling and progenitor cells are imperative requirements (Giannoudis et al., 2007; Giannoudis et al., 2008). The implanted biomaterial in vivo will encounter the cells of the immune system that will degrade the material or contain the material within a fibrous tissue. Furthermore, the surrounding tissue will provide a mechanical environment that will both affect the material as well as the cell response.

The material will have the possibility to affect stem and progenitor cells in terms of lineage fate and function. It is this wide range of parameters that in vivo models are designed to encompass. In vitro assays, on the other hand, typically, serve as screening assays that allow experimental assessment used as predictive methods for rapid screening of the host response to the biomaterial. The International Organisation for Standardisation (ISO) and ASTM International have developed standards that are specific for in vitro biocompatibility and cytotoxicity tests (Müller 2007) and for standardised assessment of biomaterials both in vitro and in vivo (F1983-14; F2721-09r14), which significantly increases the safety of the product. However, these standards are generally for medical devices and may not predict the bone regeneration of a specific biomaterial.

A raft of standardised tissue culture techniques are used to observe cell compatibility where the toxicity of the material can be measured by, for example, cell survival, metabolic activity and cell growth. The effect of the material can be studied utilising cell differentiation where expression of genes and mRNA and cell surface markers are quantified (Ko et al., 2008).

Though in vivo experiments will likely remain a critical aspect of biomaterial testing, in vitro assays need to play an increasingly important role in screening out biomaterials with inadequate properties prior to examination of more promising candidates in vivo. A key question to address is therefore: are current in vitro assessments proficient in fulfilling this role of pre-screening prior to in vivo assessment of bone regeneration? In this context, the term in vitro assessment refers both to the assay itself and the interpreted significance of the assay results that serve to inform further studies along the biomaterial testing pipeline. To address this question, the current study explores the correlation between researcher assessed, in vitro and in vivo outcomes of biomaterials tailored for bone in a European multicentre study between 8 universities that included 36 independent in vivo studies and 47 individual in vitro assays testing 93 biomaterial variables. The focus of this study is on the correlation between in vitro testing and early stage (i.e. small animal) in vivo models of bone regeneration in use across the consortium. In contrast to conventional literature based meta-analyses,
Data collection

Members from the European consortium Biodesign, comprising 8 universities in a European multicentre study, kindly collated the data (Table 1) from both published and unpublished historical in vivo datasets. The scope of the data included was defined by completed in vivo studies for the various biomaterial strategies tested. The in vitro assays, which constitute the subject of this study, were selected on the basis of their use by the member groups in the testing of their biomaterial strategies prior to or alongside these in vivo studies. The data included 36 in vivo experiments, 47 in vitro experiments and 93 tested biomaterial variables.

In vivo and in vitro outcomes for each experimental variable tested in an in vivo study were described qualitatively by the assessor on the basis of a range of expected positive and/or negative indications of regenerative outcome (e.g. high cell proliferation, evidence of cytoxicity etc.) pre-defined for each assay by the assessor. On the basis of this qualitative assessment, the outcome of each variable for each in vitro and in vivo assay conducted was scored out of 5 (1 = poor, 5 = very good).

In vitro parameters assessed for correlation

Cell differentiation

Cell differentiation towards the osteogenic lineage can be quantified by measuring the activity of the cell marker alkaline phosphatase (ALP) (McComb et al., 1979), a widely used non-specific assay for osteogenic differentiation. In this assay p-nitrophenyl phosphate is dephosphorylated by ALP into a yellow product with an absorbance that can be measured at a wavelength of 405 nm. ALP is highly expressed by osteoblasts and through the cleavage of pyrophosphate allows spontaneous mineralisation in the secreted osteoid (Millan 2013). A high activity of ALP is interpreted as a positive outcome as ALP plays a central role in the bio-mineralisation process of bone.

Biocompatibility

Several biocompatibility tests can be used for cell proliferation, cell viability, and cell attachment to distinguish material candidates that are of a biocompatible nature. A number of reagents are used and most of them are based on the same concept of measuring the metabolism by the reduction of a substrate. One common example is a tetrazolium compound that is mixed with phenazine methosulphate (MTS) (Goodwin et al., 1995). During cell metabolism, MTS is reduced by the activity of dehydrogenase to formazan that can be measured by visible light absorbance at 492 nm. Live dead staining is a widely used in vitro assay to measure the viability of cells. A fluorescent dye 5-chloromethylfluorescein diacetate (CMFDA) labels metabolically active cells and the membrane impermeable ethidium homodimer-1 labels DNA in apoptotic or damaged cells.

Gene expression

Osteogenic differentiation can be measured by quantifying the expression of specific genes expressed during osteoblastic differentiation. One of the key transcription factors is Runt-related transcription factor 2 (RUNX2) (van Wijnen et al., 2004), which at early stages induce the process of osteoblast differentiation and in later stages inhibits the same process. RUNX2 is important in skeletal morphogenesis and is involved in the expression of several bone matrix genes such osteocalcin, being an abundant protein found in bone provides useful markers to follow stem-progenitor differentiation. Genes that are expressed at later time points include, for example, osteopontin, involved in remodelling (Bruderer et al., 2014). Increased gene expression at the appropriate temporal stages is interpreted as a positive result.

Mineralisation assay

Calcium deposition of cell cultures can be quantified using alizarin red staining and serves as a measure of osteogenic differentiation, where a large amount of deposition is interpreted as a positive outcome (Dawson 1926). This in vitro assay provides evaluation of the osteoblastic differentiation of progenitor cells as well as the functionality of the differentiated cell population (Gregory et al., 2004).

Table 1. Participating laboratories in the survey.

<table>
<thead>
<tr>
<th>University</th>
<th>Group principal investigator</th>
<th>Country</th>
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<tr>
<td>AO Foundation</td>
<td>Martin Stoddart</td>
<td>Switzerland</td>
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<td>Eidgenössische Technische Hochschule</td>
<td>Ralph Müller</td>
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<td>Keele University</td>
<td>Alicia El Haj</td>
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<td>Ludwig Boltzmann Institute</td>
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<td>University College London</td>
<td>Robert Brown</td>
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<td>Uppsala University</td>
<td>Sune Larsson, Jöns Hilborn</td>
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**In vivo models against which in vitro models were correlated**

The purpose of this review article was to correlate the interpretation of in vitro results to in vivo outcomes observed for a range of biomaterials. A selection of in vivo models from the survey that had been used to evaluate biomaterials was correlated to the interpreted results of in vitro assays for the same biomaterials.

**Segmental-defect models**

Critical size segmental defects in rats and mice are frequently used to measure the osteoinductive capability of biomaterials for bone regeneration using a fixator that is either internal or external. The definition of a critical sized defect is an incapability of spontaneous healing (Hollinger and Kleinschmidt 1990). Addition of an inductive substance, that triggers bone formation, is necessary for bridging healing to occur. Einhorn et al. (1984) developed, in the 1980s, a rat segmental defect that consistently resulted in non-union when left untreated. The femoral defect was 6 mm long and stabilised with two proximal and two distal Steinmann pins. The defect was evaluated with radiographs and mechanical testing (Einhorn et al., 1984). This femoral segmental defect was later reduced to a 5 mm long segmental critical size defect to evaluate the osteogenic potential of silk scaffolds combined with either human bone marrow stromal cells (HBMSCs) or a combination of HBMSCs and bone morphogenetic protein 2 (BMP-2) (Meinel et al., 2006). The same combinations were used with the addition of pre-differentiated HBMSCs (Kirker-Head et al., 2007). Both studies assessed the healing capacity using micro-computed tomography (μCT), mechanical testing and histology.

Both Kaipel et al. (2012) and Schutenberger et al. (2012) used a 3 mm long segmental defect as a delayed union model in rats. The defect was stabilised with an internal plate fixator, while initial healing was prevented using a silicone spacer that was kept in the defect for 4 weeks after which it was removed during a second surgery. Following removal of the spacer the defect was filled with either a BMP-2 fibrin carrier or the commercial available BMP-2 collagen carrier. The same defect was used in an in vivo study to evaluate the effect of applied growth factors of angiogenesis and osteogenesis in a fibrin clot. The bone forming capacity was evaluated by X-ray, μCT and mechanical testing (Kaipel et al., 2012; Schutenberger et al., 2012). The results showed increased bone formation using BMP-2 in a fibrin clot. The study also showed that a fibrin scaffold with a sevenfold lower dose of BMP-2 could still provide equivalent results compared to the commercial BMP-2 product.

Kanczler et al., used the male MF-1 nu/nu immunodeficient mouse femur segmental defect model to study the enhancement of bone regeneration after implantation of HBMSCs seeded onto vascular endothelial growth factor (VEGF)/BMP-2 composite scaffolds (Kanczler et al., 2010) or biodegradable poly(D,L-lactide) (PLA) scaffolds (Kanczler et al., 2008) with VEGF incorporated. Bone formation was measured using μCT and histology with both materials providing enhanced regeneration of the segmental bone defect compared to groups without HBMSCs and growth factors. The same research group employed diffusion chambers that were implanted intraperitoneally in MF-1 nu/nu mice for 10 weeks. The diffusion chambers afforded interaction with the in vivo milieu without ingrowth or response from the host cells and thus allowed evaluation of seeded HBMSCs on a biomimetic collagen scaffold and BMP-2-encapsulated (PLA) scaffolds (Yang et al., 2003; Yang et al., 2004a; Yang et al., 2004b).

**Subcutaneous models**

The subcutaneous implant is a widely used model, usually, to assess the osteoconductive and osteoinductive properties of a material to develop ectopic bone. The disadvantage of the subcutaneous model is the perceived lack of clinical relevance and, typically, the absence of bone cells that can affect the potential bone formation capacity of a material. Nevertheless, the absence of local bone cells can also be advantageous and has been used for evaluation of HBMSCs that were seeded on solid hydroxyapatite and collagen scaffolds or in polysaccharide capsules (Dawson et al., 2008; Pound et al., 2006). To visualise the vascularisation of tissue-engineered constructs containing HBMSCs/bone allograft and PLA, a subcutaneous model was used in athymic mice. The constructs were impacted and implanted subcutaneously and after 4 weeks perfused in vivo with Microfil prior to μCT scanning (Bolland et al., 2008). The subcutaneous implants provide a rapid screening model for “biocompatibility” and osteo-inductivity/-conductivity and have been used for bioactive materials carrying growth factors such as Bone morphogenetic proteins (BMPs) (Kisiel et al., 2013). Several implants can be compared in the same individual giving paired data and hence the possibility to reduce the number of animals used while achieving valid information.

**Critical sized cranial-defect models**

Critical sized cranial defects (CSD) have been employed for bone material evaluation for over fifty years. As far back as 1957, Ray and Hollow described a cranial defect in rats that was treated with frozen intact bone, deproteinised bone or decalcified bone. Subsequently, Ko et al. used a 8 mm cranial defect in rats. However, the cranial defect model is technically challenging with risk to the dura mater as well as a risk of severe haemorrhage due to the presence of major blood vessels in the cranial bone (Ko et al., 2008). Ray and Holloway circumvented these issues by creating smaller defects on the lateral side of the cranium to avoid the underlying blood vessels (Ray and Holloway, 1957). Given the smaller defect size (4 mm), two defects can be generated in the parietal bones lateral to the mid-sagittal suture in the cranium of rats and mice, allowing paired analysis and thus enhancing statistical power (Meinel et al., 2005; Ventura et al., 2014).

**Femoral condyle-defect model**

The use of large animal models has also been examined. Ueng et al. created bone cavities in the lateral femoral condyles of rabbits and implanted beads of alginate mixed with PKH 26-labelled rabbit mesenchymal stem cells and vancomycin (Ueng et al., 2007). The beads of alginate...
demonstrated sustained release of vancomycin over 14 d and osteogenic differentiation of cultured mesenchymal stem cells (MSCs) in the alginate carrier matrix. The implanted MSCs contributed with newly formed bone in vivo.

Data analysis
The overall correlation between in vitro and in vivo outcomes across the entire dataset was characterised by sorting and then categorising the data according to in vitro score, before plotting the mean in vivo score obtained for each respective in vitro score category. Thus, for every biomaterial variable scoring 1, 2, 3 etc. in vitro, the corresponding in vivo scoring was listed and the mean plotted against each respective in vitro score ‘category’. The same approach was adopted with the in vivo scores, which were again categorised to obtain the corresponding mean in vitro score for correlation.

As well as an overall assessment of in vitro – in vivo correlation, the in vitro outcomes were sorted into sub-groups representing individual classes of in vitro assay. The sub-groups were, i) Group 1; alkaline phosphatase activity, ii) Group 2; biocompatibility, iii) Group 3; calcium deposition iv) Group 4 and 5; gene expression of early markers and late markers respectively (Table 2). The in vitro outcome scores of the material were subsequently correlated with the in vivo outcome scores. Further, the in vitro assay groups were combined in pairs to investigate if a combination of in vitro assays provided a better prediction of in vivo outcome over single assays for correlation.

For the purpose of the remaining part of this paper, the following terms are used as defined below: Groups consist of in vitro assay (See Table 2), which were used as parameters to correlate the predictive outcome.

Null hypothesis: No correlation exists between in vivo and in vitro outcomes.

Hypothesis: Specific in vitro parameters or a combination of in vitro parameters can be used to predict material in vivo outcomes.

Correlation
Pearson’s correlation was used to test for significant linear relationships between the in vitro and in vivo outcome (n > 5). Coefficients of determination (R²) delineating the percentage of shared variance are presented and a p-value of < 0.05 was considered significant.

Sensitivity and specificity
The data for each in vitro assay groups was split into quartiles to distinguish false positives, false negatives, true positives and true negatives where a positive result was defined as one that scored > 2.5 and a negative result was defined as one that scored < 2.5 (Fig. 3a). Fisher’s exact test was performed to measure the sensitivity and specificity of the various groups. A confidence interval of 95 % was used.

Results and Discussion
Despite considerable consensus in how assays were interpreted, the current analysis demonstrated no significant overall correlation between in vitro outcomes and in vivo outcomes.

The mean in vitro scores revealed a trend of covariance to in vivo scores with 58 %. The mean in vivo scores shared 51 % of variance when correlated to the in vitro categories (Fig. 1a). Analysis of the different in vitro techniques; biocompatibility, cell differentiation, gene expression of early markers, gene expression of late markers and calcium deposition demonstrated a covariance of less than 10 % (Fig. 1b-f). To determine if combinations of in vitro assays could predict the in vivo outcome, a selection was made that included materials evaluated by more than one in vitro assay. The medians of the combined in vitro scores were subsequently correlated to the in vivo outcomes (Fig. 2a-f). On analysis, less than 10 % covariance was observed except for the combination of Group 1; alkaline phosphatase expression with Group 2; biocompatibility assays, where a 95 % covariance was observed (Fig. 1a).

Our approach has its limitations. Any cross centre study, especially adopting a retrospective approach, is subject to the significant challenge of inevitable variation in protocols, reagents and cell source etc. between laboratories. Importantly, the main readout of the current study, the correlation between in vitro and in vivo outcomes will remain fairly robust against such variation as the point of comparison is not between the assays conducted across the various groups, but between the in vitro and in vivo stages of biomaterial testing undertaken in each individual laboratory. Perhaps more problematic is the inevitably limited scoring system required to tabulate the large variety and complexity of the assays conducted. For example, we reduce a complex readout such as osteogenic gene expression to a score of high and low expression of early and late markers. This is indeed a significant limitation.

| Table 2. In vitro assays with participating laboratories and numbers of separate studies per in vitro assay. |
| Assay | Parameter name |
| 24 separate Alkaline Phosphatase Assays from 5 laboratories | Group 1 |
| 14 Biocompatibility Assays from 4 laboratories | Group 2 |
| 8 Calcium Deposition data sets from 2 laboratories | Group 3 |
| 20 Gene Expression data sets of early markers from 3 laboratories | Group 4 |
| 22 Gene Expression data sets of late markers from 3 laboratories | Group 5 |
of the current approach, but such broad-brush stroke assessments of performance reflect the conclusions often drawn from in vitro assays across the biomaterial literature. Such assessments thus serve as the hypotheses to be tested by our approach. Similarly, the qualitative assessment of each assay outcome was conducted by the groups that undertook the original research, raising possible concerns about subjective bias in the assessment of the results. This needs to be acknowledged as a clear limitation in the interpretation of the in vitro outcome itself and subsequent in vivo significance, but it is precisely such interpretations (we contend) of the success or failure of the biomaterial in the in vitro assays that currently form the basis for future in vivo testing and translation. Thus, this very limitation further serves the purpose of our study to test the decision making process underlying the biomaterial testing pipeline from in vitro to in vivo assessments and, it can be noted, justifies the contention of this review that such a lack of correlation is indeed surprising.

This surprisingly poor correlation between in vitro and in vivo assessments of biomaterials could be due to a number of further factors intrinsic to the assays themselves. These include cell choice, cell line, cell passage, and cell culture protocols, which while broadly similar between laboratories, can result in significantly different data outcomes. In a literature study, Bara et al. described the differences between naive MSCs and MSCs cultured in vitro for expansion. The authors reported a large effect of the isolation and culture parameters that gave opposing results in two clinical trials, using protocols with differences in density media, centrifugation steps and the combination of media and serum. Interestingly, the seeding of whole bone marrow had a positive effect on Colony forming unit (CFU) efficiency and telomere length of the
MSCs. Furthermore, a lower seeding density enhanced proliferation while the application of autologous serum had a positive effect on MSC stability and maintenance of the naive state. The sensitivity of these parameters and their significance for clinical outcome thus underlines the importance of standardisation of protocols in order to dissect differences in the response to biomaterials against inherent differences in MSC phenotype due to various expansion protocols (Bara et al., 2014).

A further potential confounding factor, particularly for in vitro assays using primary cells, is the known issue of donor variation (Georgi et al., 2015). To try and overcome the confounding influence of donor cell variation is the evaluation of materials using cell lines. While primary cells would appear likely to better approximate host responses, including, as above, host variation, such variation in the absence of large multi donor analyses, makes comparison of cell-biomaterial responses between studies difficult. A key advantage afforded by the implementation of cell lines is the homogeneity of the cell population allowing, at least at the early stages of the biomaterial testing pipeline, relatively straightforward comparison of results across studies and laboratories. Furthermore, cell lines can often allow differentiation stage-specific responses to biomaterials. For example, one study comparing the ability of various cell lines to mimic the response of mature osteoblasts found the MC3T3-E1 cell line to predict primary osteoblast responses in vitro with high fidelity (Czekanska et al., 2012).

Fig. 2. The groups were combined in pairs to investigate if the combination could predict the in vivo outcome. a) Combined in vitro score of Group 1; alkaline phosphatase and Group 2; biocompatibility (n = 5); here a significant covariance of 94.5 % was seen with a p-value of 0.0055. b) Combined in vitro scores of Group 1; alkaline phosphatase and Group 3; calcium deposition (n = 5). e) Combined in vitro score of Group 1; alkaline phosphatase expression and Group 4; gene expression of early markers (n = 11). d) Combined in vitro score of Group 2; biocompatibility and Group 3; calcium deposition (n = 5). e) Combined in vitro score of Group 2; biocompatibility and Group 4; gene expression of early markers (n = 5). f) Group 4; gene expression early markers combined with Group 3; calcium deposition (n = 7). All group combinations except for Group 1/Group 2 and Group 1/Group 3 shared covariance of less than 10 %.
Nevertheless, even accounting for the variations in experimental protocols and cell sources for each assay method, almost all in vitro assays demonstrated the ability to correctly identify positive outcomes (i.e. true positives) to a slightly greater extent than false positives (i.e. incorrectly predict a positive outcome). The statistical power of the in vitro assay groups was variable, thus affecting the ability to interpret the results accurately. However, increasing the number of studies per in vitro assay group to increase the power of each predictive model may not necessarily improve the specificity of the model as evidenced by Fig. 1a, e and f. Fisher’s exact test was performed to further measure the sensitivity and specificity on the various groups; all \( p \)-values obtained were of statistical non-significance (Fig. 3-4). One approach to improve the predictability would be to develop a system of metrics based on the combined score achieved through a series of in vitro assays. Thus, for example, the combined in vitro tests of biocompatibility and alkaline phosphatase expression had a strong positive correlation, indicating a potential benefit of in vitro assay combinations. The combination of groups demonstrated the ability to detect true positives to a greater extent than false positives in all groups.

It is self-evident that a large selection of in vivo models are used to assess the performance of biomaterials tailored for bone. Each in vivo model is often slightly modified for the purpose of the particular study and to suit the properties of the biomaterial tested. Thus, the large number of in vivo models available can make direct comparison difficult. Standardised and validated defects with defined parameters of in vivo outcome would facilitate direct comparison and minimise the number of animals used (Kilkenny et al., 2010; Reichert et al., 2009; van Griensven, 2015). It is also necessary to appreciate that not only do the in vivo models differ, but also definitions of successful bone regeneration differ between each study.

We have highlighted the surprisingly poor correlation between in vitro success or failure and in vivo success or failure in biomaterial testing for bone repair. It should also be noted that this challenge may be relatively modest compared with the subsequent challenges of achieving successful translation from small to large animal models and from preclinical studies into clinical trials (van...
Fig. 4. The groups were combined in pairs to investigate if a combination could predict the in vivo outcome. Each study of the groups was split into quartiles to sort them into percentage of false positives, false negatives, true positives and true negatives where a positive result was one that scored > 2.5 and a negative result one that scored < 2.5. 

a) Group 1; alkaline phosphatase and Group 2; biocompatibility (n = 5) detected true positives and true negatives, b) Group 1; alkaline phosphatase and Group 3; calcium deposition (n = 5) detected 20% false positives and 80% true positives. c) Group 1; alkaline phosphatase expression and Group 4; gene expression of early markers (n = 11) detected a large amount of false positives 55% compared to 36% true positives and a small amount of false negatives was also detected. Both d) Group 2; biocompatibility and Group 3; calcium deposition (n = 5) and e) Group 2; biocompatibility and Group 4; gene expression of early markers, detected a majority of true positives 60%. f) Group 4; gene expression early markers combined with Group 3; calcium deposition (n = 7) had a slight majority of 57% of true positives. The combination of groups demonstrated the ability to detect true positives to a greater extent than false positives in all groups. Fisher’s exact test was performed to further measure the sensitivity and specificity on the various groups; all p values obtained were of statistical non-significance and thus inconclusive.

Griensven, 2015). Critically, at each stage, increased cost as well as surgical and physiological complexity, challenge reproducibility as well as predictive power (Reichert et al., 2009). Hackam and Redelmeier explored the translation of research from animals to humans and concluded that only about a third of highly cited preclinical articles were later translated to human trials (Hackam and Redelmeier, 2006). One promising approach to addressing these inherent limitations of large animal models has been the development of humanised animal models. Humanised animal models may, finally, serve to improve the predictive power of pre-clinical assessments (Holzapfel et al., 2015).

Conclusion

While we have here noted the weakness of several widely used in vitro measures of biomaterial success, it is important to emphasise the vital importance of the application of in vitro assays for biomaterial testing for bone regenerative medicine. The growing number of potential biomaterials for application in bone regeneration strategies warrants increased research investment in the development of early stage assays predictive of in vivo success or failure in order to streamline the biomaterial testing pipeline towards the goal of clinical translation. The current inadequacies of our in vitro assays highlighted here, will we hope further underline the urgency of this research imperative and, critically, stimulate the development of novel approaches to biomaterial testing and appropriately characterised pipelines with measurable sensitivity and specificity for translatable in vivo outcomes. In this way, we hope the rather long-awaited therapeutic promise of bone regenerative medicine will begin to be realised.
Acknowledgements

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Editor’s Notes: All questions/comments by the reviewers were answered by text changes. There is hence no Discussion with Reviewers section.

Scientific Editor in charge of the paper: Joost de Bruijn.